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## DEFENCE RESEARCH ESTABLISHMENT OTTAWA

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*Milsatcom Group*
*Space System & Technology Section*

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# ABSTRACT

Precise range and positioner alignment are required for the accurate measurement of the radiation characteristics of microwave antennas using a spherical antenna measurement range. This report presents a custom designed system and novel techniques developed at DREO, based on optical instrumentation, to conveniently measure and monitor both the range alignment and the orthogonality and intersection of the multi-positioner spherical system axes. This system is an indoor spherical test range located in an anechoic chamber. The alignment hardware consists of several levels, an electronic theodolite with built-in autocollimation capability, and a unique target mirror assembly with the target viewable from both sides. A hand-held programmable calculator is also used to calculate angular positions and distances. Numerous techniques and procedures developed for optical alignment are described in detail. The user is guided through each step required for a precise optical alignment.

# RÉSUMÉ

Les mesures d'antennes micro-ondes utilisant un système de positionneurs sphériques demandent un alignement très rigoureux de l'installation de mesure, en particulier des axes des positionneurs afin d'obtenir des mesures précises des caractéristiques du champ électromagnétique irradié. Ce rapport présente un système fait sur mesure et des techniques d'alignement originaux développés au CRDO. Ces techniques, basées sur un instrumentation optique conventionnel, sont utilisées pour mesurer et ajuster convenablement l'alignement du système de mesure et assurer l'orthogonalité et l'intersection des axes d'un système sphérique à plusieurs positionneurs. Ce système de mesure sphérique intérieur est situé dans une chambre anéchoïque. Le matériel requis comprend des niveaux à bulles, un théodolite électronique avec autocollimation, et un miroir réglable muni d'une cible visible des deux côtés. Un calculateur programmable est aussi utilisé pour calculer angles et distances à partir des lectures du théodolite. De nombreuses techniques et procédures développées pour l'alignement optique du système sphérique de positionneurs sont amplement décrites. L'usager est guidé à travers toutes les étapes requises pour obtenir un alignement optique précis.

# EXECUTIVE SUMMARY

This report describes a custom designed system and novel techniques developed at DREO to perform a precision alignment of a spherical antenna range using optical instrumentation. Adequate precision has been obtained to allow near-field measurement of antennas up to the millimeter-wave region. These types of antennas require precise range and positioner alignment for accurate RF measurements. The spherical positioner system is made up of three antenna positioners. Two positioners, mounted in a roll-over-azimuth configuration and a third one supporting the probe to maintain the polarization orientation during the measurement process constitute the spherical positioner system. The optical equipment used for the alignment includes precision levels, an autocollimation theodolite, mirrors with a high precision target, and alignment and positioning devices for supporting optical tools and positioners. Significant modifications and improvements were made to the optical hardware, particularly the target mirror, and also to the rail system and positioner carriages, and to the theodolite support system.

Novel alignment techniques developed include: the way that the equipment has been integrated into a system to achieve the desired accuracy; the overall alignment concept; methods to determine the location of axes of rotation; and the development of methods to align the positioner axes such that they are collinear, or perpendicular and intersecting. Major characteristics of these techniques include the precise setting of the intersection of the axes to a fraction of a millimeter, the setting of axes orthogonality to within a few arc-seconds, and the direct measurement of the roll and probe axes stability under motion.

The description of the measurement facility and a preliminary discussion of the degrees of freedom for the adjustment and alignment of the test positioner system introduce the subject. It is followed with a discussion of the optical alignment tools. In order to avoid repeating the description of the optical alignment procedures, several common alignment operations, which are part of the alignment activities, are brought together and described separately at the beginning. The description of techniques in the usage of the levels, techniques for the theodolite setup in autocollimation mode for the adjustment of a mirror normal to an axis and for the alignment of two axes parallel to each other, and methods in the installation and adjustment of the spindle target mirror assembly, are also included. Mainly, the common operations include the adjustment of the optical axis parallel to the rails, the determination of the verticality of the azimuth axis of rotation, the installation and adjustment of the mirror assembly, and the adjustments to make two axes parallel and coincident. Discussions on positioner spinning techniques and static methods for mirror adjustment and axis alignment are also included.

Six main procedures for the optical alignment of the spherical antenna measurement system were developed. These include the selection of a unique plane perpendicular to the positioner system support rails; the alignment of the optical axis of the theodolite parallel to the rails; the alignment of the axes of the azimuth positioner, of the roll positioner and of the probe positioner; and the alignment of the optical axis of the theodolite on the range axis. The techniques used to align the probe antenna and the antenna under test are also covered.

The method presented in this report is a precision means of optically setting the intersection and orthogonality of the three appropriately configured positioner axes.

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# 1 - Introduction

## 1.1 General Description of the Problem

The design and characterization of high performance antenna systems at microwave and millimetre wave frequencies requires the sampling of phase and amplitude data. To obtain accurate measurement data, good control of the positioner geometry is required. There is a requirement to devise a method to easily set and verify the axis intersection and orthogonality of the antenna test positioners. The function of an antenna test positioner is to move an antenna in such a manner that a "probe" horn or antenna can measure the RF radiation emitted in the direction of interest.

There are three positioners in the spherical measurement system, each with its own axis of rotation which must be aligned and must intersect each other in a prescribed manner. The axes of the roll positioner and of the probe positioner, the AL-560 and AL-360, manufactured by Orbit Advanced Technologies, must be horizontal, i.e. normal to gravity, parallel and coincident, and form what is described in Figure 1, the range axis. The axis of rotation of the AL-860 azimuth positioner, which defines the vertical axis, must intersect the range axis at right angles, i.e. parallel to gravity. The method used to perform the adjustments to align the axes and to determine their intersection and orthogonality is optical, and requires special instrumentation such as a theodolite with built-in autocollimation capability, special target mirrors viewable from both sides, levels to establish the correct axis direction and position, and the positioners and theodolite alignment fixtures to implement corrections and adjustments.

## 1.2 Layout of the Report

The description of the optical alignment of the spherical antenna measurement system is covered in three main chapters. In chapter 2, the topic is introduced by giving definitions and descriptions of equipment and procedures. In chapter 3, the methodologies and common alignment operations are described. In chapter 4, a detailed description of each step required to perform the optical alignment is given, referencing, when required, the common alignment operations described in chapter 3.

Chapter 2 is introduced with a description of the measurement facility (section 2.1), followed by a discussion of the numerous degrees of freedom for the adjustment and alignment of each piece of equipment comprising the test positioner system (section 2.2). This section also includes a description of the main tools used for the optical alignment (section 2.3) including: the electronic theodolite and its built-in autocollimation capability; the theodolite stand and its various adjustments; the two-way spindle target mirror assembly and the specially designed target mirror where the target is etched in the single reflective coating on the top of the mirror to make it visible from both sides; and, the multiple positioner alignment fixtures.

Chapter three follows with the description of the methodologies and the common alignment operations, in the use of levels, of the theodolite in telescopic and in autocollimation

mode, and, of the spindle target mirror assembly. Optical techniques such as the determination of the direction of the rails, or the vertical orientation of the azimuth axis, or the autocollimation method used to adjust the mirror normal to an axis are also presented.

The methods, procedures or common operations described include: the adjustment of the optical axis parallel to the rails; the adjustment of the azimuth axis to be vertical, parallel to gravity; the installation and adjustment of the mirror assembly; and the adjustment to make two axes parallel and coincident (either the positioners or the theodolite). Two methodologies for aligning two axes parallel to each other are presented.

Chapter 4 describes the optical alignment procedures. In each procedure description, references are made to the common optical alignment operations described in chapter 3. A description of the degrees of freedom of the sub-system in question is included with each procedure. However, before describing the optical alignment procedures, a detailed discussion of the initial installation of the azimuth positioner is given in section 4.2. This is a very critical adjustment step required for the success of the alignment exercise. This is followed by the adjustment of the support mast of the roll positioner to determine the correct position of the antenna under test (AUT) with respect to the azimuth axis (section 4.3). Because it is required for the above adjustment, a procedure to determine the location of the phase centre of an antenna was developed and its implementation is described in Appendix B. A spreadsheet algorithm for the determination of the location of the phase centre of an antenna is also described.

The six main optical procedures for the spherical antenna measurement system, along with the techniques for the alignment of the probe antenna and of the AUT along the range axis are covered in section 4.4. These procedures include: the selection of a unique plane perpendicular to the positioner system support rails; the alignment of the optical axis of the theodolite parallel to the rails; the alignment of the axes of the azimuth positioner, of the roll positioner and of the probe positioner; and the alignment of the optical axis of the theodolite onto the range axis. A computer program for a hand-held calculator is described in Appendix A. Its purpose is to help, during the alignment exercise, in the calculation of angular positions and distances. The narrative includes theory of operation, user instructions and a program listing.

# 2 - Definitions and Description of Procedures

## 2.1 Description of the Spherical Antenna Measurement System

The spherical antenna measurement system in the DDARLing (DREO-DFL Antenna Research Laboratory) facility is located in the David Florida Laboratory (DFL) of the Canadian Space Agency. The facility includes an anechoic chamber, spherical and planner antenna positioners, receivers, computers and all the necessary equipment to make antenna measurements from 2 GHZ to 62.5 GHz. A more detailed description of the facility including the spherical measurement system and its data collection software can be found in Reference [1]. The planar positioner is for near-field measurements while the spherical system can be used for either near-field or far-field measurements.

The spherical antenna measurement system, located inside the anechoic chamber, is comprised of three positioners manufactured by Orbit Advanced Technologies, an AL-860, an AL-560 and an AL-360. In this report, these three positioners are referred to, in sequence, as the azimuth positioner, the roll positioner, and the probe positioner. The first two positioners, the AL-560 and the AL-860, are configured as a roll-over-azimuth positioner for supporting the AUT, and the AL-360 is the probe positioner, as seen in Figure 1. The function of the positioners is to move the AUT and the probe (horn) in a manner to enable the measurement of the RF radiation pattern of the AUT in a particular direction of interest. To accomplish that, the positioners must be precisely aligned. The positioner geometry must be well controlled so their axes of rotation are aligned in a prescribed manner. This report describes a method to easily and accurately set and verify the intersection and orthogonality of the axes of an antenna test positioner system.

The stability of the spherical system is ensured by a rigid and heavy steel structure composed of steel I-beams, wheeled carriages for the positioners, and support rails. It is supported on legs that penetrate the chamber floor, making direct contact with the concrete floor below. This structure, which supports the positioners and the alignment theodolite, was installed to improve the accuracy of measurement by reducing the alignment errors and providing better isolation from the building vibrations.

It can be seen in Figure 1 that alignment fixtures have been installed under all positioners to facilitate the adjustment of the angular orientation and the linear translation of the rotational axes of the positioners. The AL-860 is fixed on its carriage and cannot be moved laterally, but its three adjustable support jacks allow for sufficient orientation adjustment to align its axis of rotation, the azimuth axis, to be parallel to gravity. The AL-560 has an alignment fixture inserted between its base and the supporting mast. The fixture has been designed with three degrees of freedom for adjustment: pitch, yaw, and linear transverse translation. No translation of the AL-560 in the vertical direction is available. The AL-360 axis also has a similar alignment fixture, but with the addition of a device for fine height adjustment.

The theodolite, used for the optical alignment of the measurement system, is mounted on a stand which is fixed at the base to the rails support structure. Being fixed to the rails system with the positioners allows for more accurate alignment, making them independent of vibrations or floor movements. The theodolite stand has two vertical adjustments possible: a coarse adjustment and a very fine one by means of an ultra-precision lift providing precisely controlled vertical motion. The stand is also equipped with a precision slide which provides a substantial travel for horizontal displacement of the optical axis.

The adjustment devices, introduced above and illustrated in Figure 1, are the main components required for the optical alignment of the three positioners of the spherical measurement system. The AL-360 and the AL-560 axes, the probe and roll axes, must be aligned horizontal and coincident, and as such make up the range axis. The AL-860 axis, the azimuth axis, must be aligned vertical and intersect the range axis at right angle.

## 2.2 Degrees of Freedom for the Alignment of the Spherical System

### 2.2.1 Degrees of freedom and Coordinate System

The alignment of a complex test positioner system such as the one described in Figure 1, which include many components, presents several degrees of freedom of adjustment and settings for the alignment of the axes of rotation, and the positioning of the AUT and probe on the range axis. Figure 2, displays the different elements of the spherical system and lists the numerous degrees of freedom available for the adjustment of the rails, the positioners, the AUT, and the probe using a theodolite. There are 29 degrees of freedom listed in total. However, not all of them represent parameters requiring adjustments. Some of them are pre-determined due to hardware restriction and as such are used as reference. Others are determined by gravity, but most of them are adjusted using the theodolite and the alignment fixtures installed on the various towers and stands.

The insert in Figure 2 displays the coordinate system used for the description of specific angles and directions. In particular, they are the pitch angle $\alpha$ and the yaw angle $\beta$, which are used to describe, among other things, the angular adjustments carried out with the alignment fixtures to align an axis of rotation in a specific direction, there is also the roll angle $\gamma$ which is used to described one of the angular adjustment required to align the azimuth axis parallel to gravity. The x and y axes indicate the vertical and horizontal directions. The vertical x-axis is oriented parallel to the gravity, the transverse y-axis is normal to the direction of the rails and the longitudinal z-axis is along the rails. The x-z plane is a vertical plane parallel to the longitudinal rails direction and located approximately mid-way between them. The range axis is, by definition, on this plane.

From the three-dimension geometry, it is known, with reference to Figure 2 coordinate system terminology, that:

i. any object in space can be defined by 6 degrees of freedom: x, y, z, pitch, roll, and yaw;

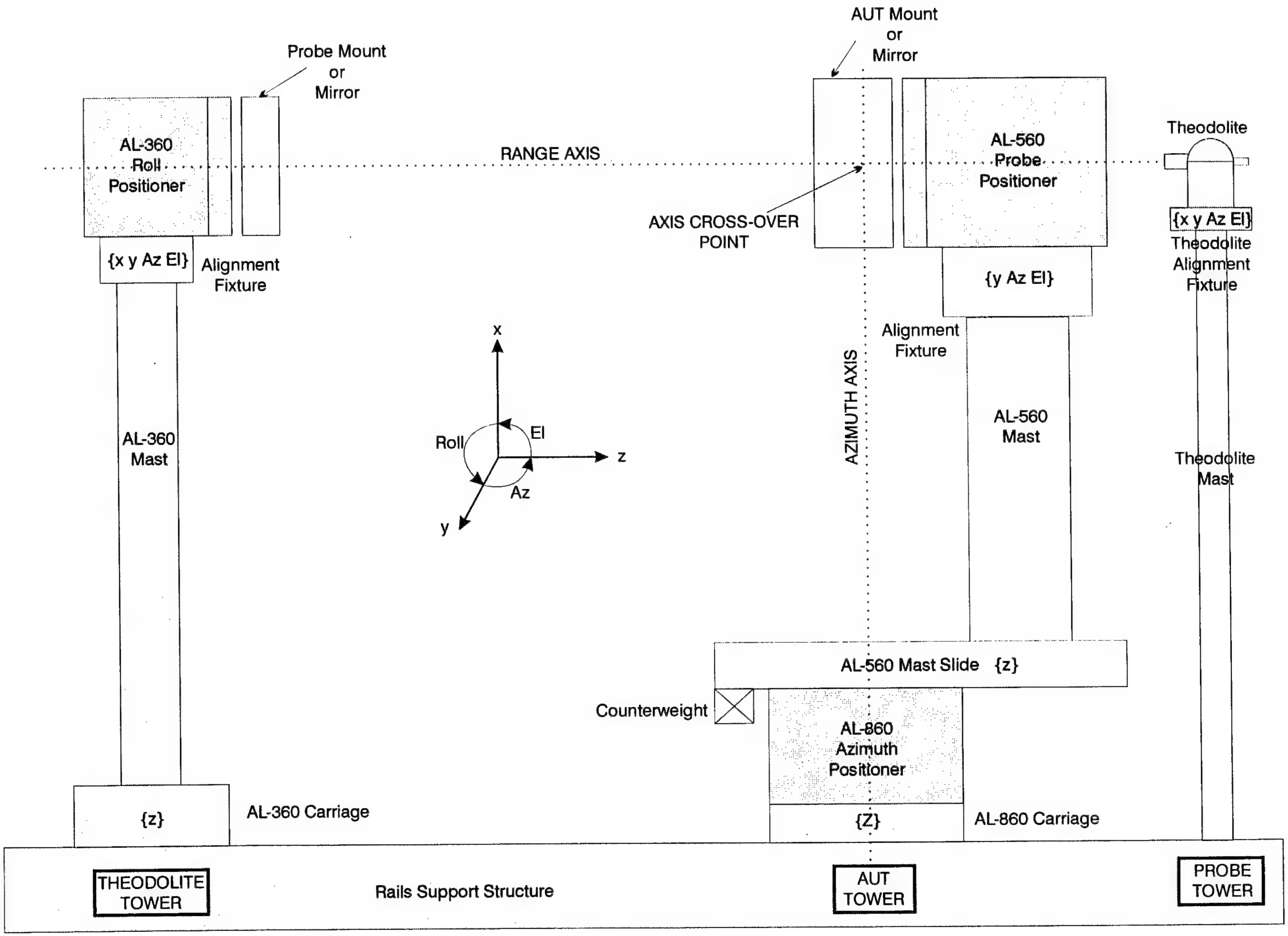



Figure 1 - Spherical Positioner System

ii. any axis can be uniquely defined by 3 degrees of freedom, pitch, roll, and yaw;

iii. any direction can be uniquely defined by 2 degrees of freedom, pitch, yaw.

In this section, the degrees of freedom of the measurement system will be reviewed and briefly explained. Each degrees of freedom in question will be hi-lighted between parentheses, as illustrated in Figure 2, for example **($\beta_R$, $y_R \leftarrow$ REF)** to mean that the direction $\beta_R$ and displacement of the rails $y_R$ are taken to be the reference values. This will be done in the approximate order in which they will be used, in the parameter adjustment sequences, for the optical alignment of the spherical system. To achieve the alignment of the spherical system, several operations must be performed to determine the location of objects, the orientation of the axes of the positioners, and the directions of items such as the rails. The process described below in paragraphs 2.2.2, 2.2.3 and 2.2.4 is a very brief overview of the alignment process using the degrees of freedom identified in Figure 2 to specify the key parameters affecting the location of objects, axes, and directions. This process insures the coincidence of the AUT roll and probe positioner axes and their intersection and orthogonality with the AUT azimuth axis. The rest of Section 2.2 must be read referring to Figure 2.

### 2.2.2 The Rails ($\beta_R$) and Theodolite ($\beta_T$) Direction

Because some antenna measurement or alignment methods require that the probe be moved in the longitudinal direction (z), the rails direction must be determined first and the theodolite azimuth 0° reference be set and locked in that direction. The direction of the rails cannot be changed; it is thus used as a reference for the range axis direction determination **($\beta_R \leftarrow$ REF)**. When the probe carriage is moved forward on the rails, the probe axis must stay on the range axis. When the probe and roll axes are correctly aligned, they form the range axis. It is one of the goals of the alignment process to make these two axes parallel and coincident.

The process of finding the rails direction and setting the theodolite **($\beta_T \leftarrow$ Rails)** to point in that direction will define several possible vertical planes, each perpendicular and parallel to the rails. The various axes making the range axis and the azimuth axis will coincide and intersect on one of the vertical planes after the alignment process execution.

### 2.2.3 The Azimuth Positioner Orientation ($\alpha_8$, $\gamma_8$) and the Theodolite Elevation and Translation ($\alpha_T$, $y_T$)

The AL-860 axis may be set vertical, or parallel to gravity, by changing only the pitch and roll angles **($\alpha_8$, $\gamma_8 \leftarrow$ Gravity)**. These angles are the angles that the azimuth axis makes with the horizontal plane. This is done by adjusting the jacks supporting the AL-860 azimuth positioner on the carriage so that the platen is horizontal at all azimuth angles. The AL-860 transverse $y_8$ parameter cannot be changed however, because its value is set by the rails geometry **($y_8 \leftarrow$ Rails)**. This results because the position of the AL-860 positioner on its carriage cannot be changed, nor can the position of the rails on which the carriage rides be changed. Once the AL-860 azimuth axis is set, only one vertical plane remains to reference the axes. It is the plane that the azimuth axis

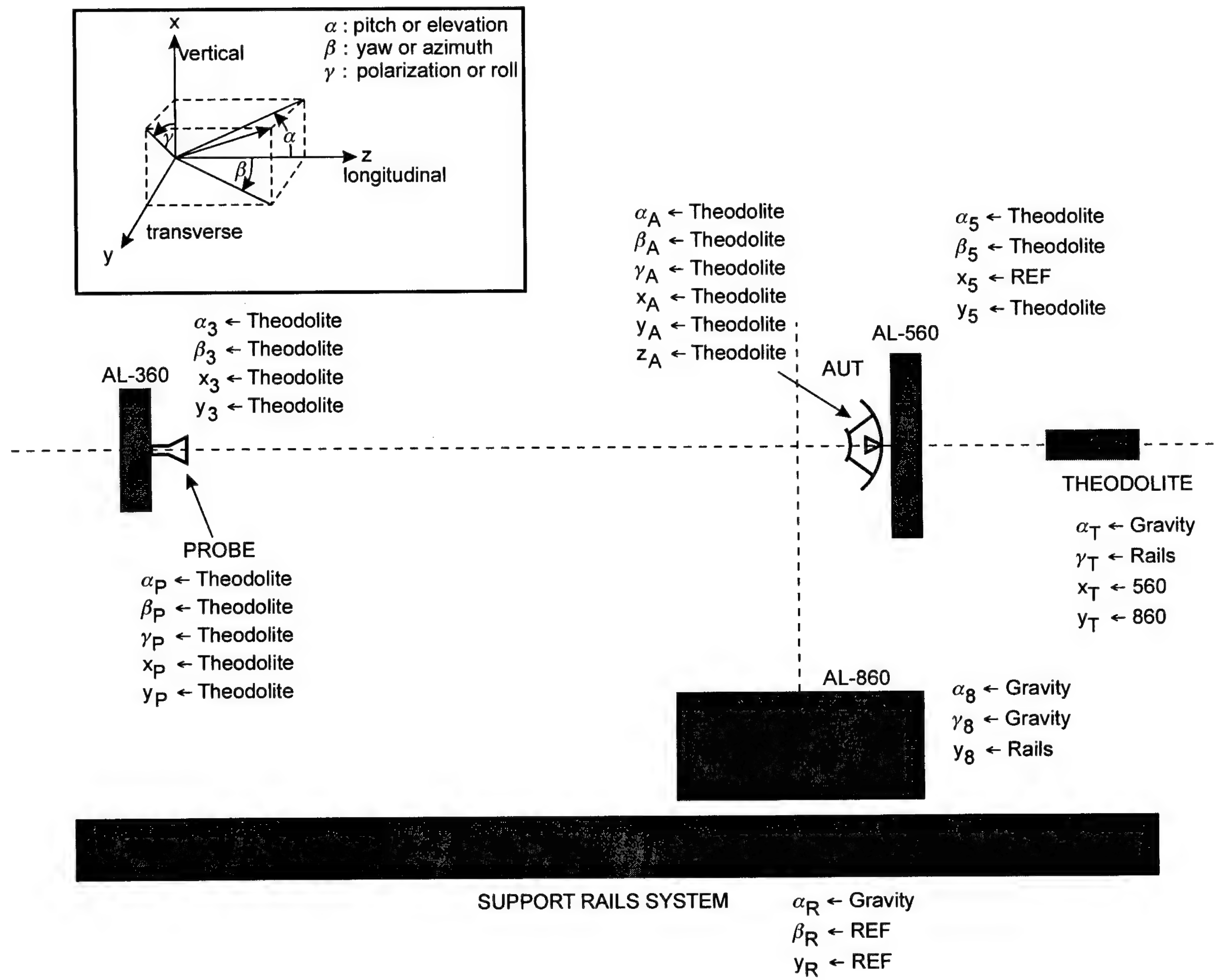



Figure 2 - Degrees of Freedom in Spherical System

intersects. The theodolite can then be moved laterally, maintaining its pointing direction, to place the optical axis of the theodolite on the selected plane **($y_T \leftarrow$ 860)**. The theodolite vertical (or elevation) setting is also set to 0° (for a horizontal line of sight), so the optical axis, oriented now normal to gravity **($\alpha_T \leftarrow$ Gravity)**, is intersecting with the vertical axis at right angle.

### 2.2.4 The Roll ($\alpha_5$, $\beta_5$, $y_5$ ) and Probe ($\alpha_3$, $\beta_3$, $x_3$, $y_3$) Positioners Alignment and the Theodolite ($x_T$) Vertical Translation

The AL-560 axis is then oriented parallel to the optical axis and translated laterally to coincide with the vertical plane (or the optical axis), **($\alpha_5$, $\beta_5$, $y_5 \leftarrow$ Theodolite)**. The AL-560 axis has no vertical adjustment, so the actual position of the roll axis defines the range axis height **($x_5 \leftarrow$ Ref)**. The theodolite is moved vertically **($x_T \leftarrow$ 560)** for coincidence of the optical axis with the roll axis. At this point the optical axis is on the range axis and the theodolite translation stages are locked into place and not to be moved again. The optical axis will be used in the next step as a reference to orient and align the AL-360 axis. Using a similar method, the AL-360 axis is aligned coincident to the optical axis or the range axis by using the angular, transverse and vertical adjustment stages **($\alpha_3$, $\beta_3$, $x_3$, $y_3 \leftarrow$ Theodolite)**.

### 2.2.5 The AUT ($\alpha_A$, $\beta_A$, $\gamma_A$, $x_A$, $y_A$, $z_A$) and Probe ($\alpha_P$, $\beta_P$, $\gamma_P$, $x_P$, $y_P$) Alignment

Once the positioner axes are aligned, the probe and the AUT are mounted on the positioners and aligned to the range axis. If the antenna mounting hardware is specialized enough for antenna orientation, 5 degrees of freedom for the probe and 6 for the AUT could be available for alignment of the antennas on the range axis. The present mounting hardware has limited adjustment capability but has been precisely machined to limit, at best, displacement and orientation errors about the range axis. These errors, however, can be measured very precisely with the theodolite.

The actual AUT mounting plate allows for some adjustment in the z-direction either by changing the support post length and/or selecting, when possible, one of the waveguide flanges from the AUT circuitry for attachment to the plate. This constitutes a coarse adjustment. A finer adjustment, with an accuracy of a few mm, is possible by relocating the base of the AL-560 mast. However, this brings a structural change to the positioner geometry and therefore it must be done only before starting the alignment process. This alignment in the z-direction is required because best measurement results are obtained when the AUT is positioned so that its phase centre intersects with the vertical axis. This may be partially achieved by doing the above adjustment. It is therefore possible to adjust the position of the AUT in the z-direction, but not very precisely.

## 2.3 Tools for optical alignment

Many of the alignment tools and devices have already been introduced above in the previous section. Each are listed below and described briefly. They consists of the following:

i. leveller fixtures mounted under the three AL-860 positioner feet. They consist of three support jacks placed under the feet of the positioner, 120° apart. These devices allow for sufficient orientation adjustment to align the axis of rotation to be perfectly vertical and

parallel to gravity. Each jack has a vertical adjustment range of up to 10 mm;

ii. precision levels with 10 sec accuracy or better. They are used for the azimuth axis vertical alignment;

iii. autocollimating theodolite and stand with horizontal and vertical linear adjustment provisions including a precision lift and a precision slide;

iv. two-way spindle target mirror assembly designed to magnetically attach to the end of a shaft spindle or the centre of a positioner platen. The assembly has a centre thru hole which allows the viewing of the mirror from the back;

v. a specially designed target mirror, with the target visible from both sides. It replaces the original mirror, of the above assembly, which has an opaque target visible only from the front side. This allows the use of the target mirror assembly where the target can be viewed from both sides;

vi. alignment fixtures mounted under the AL-360 and the AL-560 positioners to give 3 degrees of freedom of adjustment;

vii. vertical adjustment fixture using sliding wedges for the AL-360 vertical translation with a range of 1.92 mm;

Some of these tools require a more detailed description. The theodolite, the theodolite stand, the spindle target mirror assembly, and the positioners alignment fixtures are the subject of the following paragraphs.

### 2.3.1 Theodolite

The theodolite, illustrated in Figure 3, is a Zeiss ETH 2 electronic precision theodolite with a bright line built-in autocollimation feature. The ETh 2 instrument [2] combines the flexibility and ease of operation of state-of-the-art electronics. It provides high-angle measurement accuracy by the two-axis compensator for automatic correction of vertical axis error and diametral circle scanning for automatic elimination of circle eccentricities. The theodolite has three large keys to control all measuring and computational functions. Four easy-to-read liquid crystal digital displays at both the front and rear of the instrument show measuring results and the current program. Illumination for display and reticule make it easy to take accurate measurements in unfavourable light.

The telescope has a magnification of 30X with a shortest focussing distance of 1 m. The accuracy in both horizontal (azimuth) or vertical measurement is .5" with a minimum reading of 1". A good selection of angle units and vertical reference systems are available, but for the purpose of

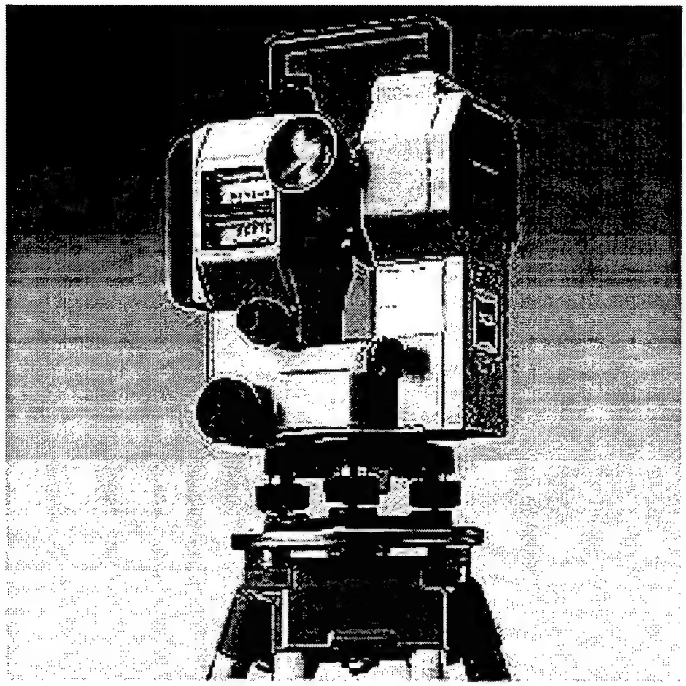


Figure 3 - ETh 2 Theodolite

optical alignment the 360° DMS (degrees, minutes, seconds) units and the vertical angle reference was retained. With the 360° DMS unit, the measurement angle is displayed in Degrees, Minutes and Seconds format, so when the instrument is pointed to an azimuth of 0°, turning the instrument to the right, angle reading increases from 0°, turning toward the left, the angle decreases from 360°. With the vertical angle vertical reference, the vertical angle reading is 0° when the telescope line of sight horizontal, going toward +90° when it is oriented upward, and toward -90° when oriented downward.

The theodolite has a bright light (lit cross) built-in autocollimation. Autocollimation is an optical procedure [3][4] in which the projected image of a lit cross, inside the telescope, is projected back from an autocollimation mirror upon the cross-hair. This system produces a contrast rich autocollimation image even at long distance. The coincidence of the reflected illuminated cross and the reticule is established easily and precisely. The principle of reflection of light is utilized to precisely position objects on a reference line, to set out accurate right angles or, to measure deviations. Autocollimation is utilized when precise angular accuracy is necessary.

For Autocollimation, the bright light is turned on, the theodolite is focussed at infinity and parallel "collimated" light rays are projected toward an autocollimation mirror. This mirror must be front surfaced and optically flat to produce the necessary accuracy. The line of sight is aimed at the reflection of the lit cross and since the telescope is focussed at infinity the lit cross is in focus. When the line of sight of the telescope strikes the mirror, the bright light will be reflected at an angle if the mirror is not perpendicular to the line of sight as demonstrated in Figure 4 [3]. The autocollimation mirror placed on the part being positioned must be in direct line and perpendicular to the line of sight. In this way the observer looks through the telescope and sees the cross-hairs of the instrument centred on the bright cross. Autocollimation is used to established a series of parallel planes and no error can be introduced by the curvature of the line of sight because it is always focussed at infinity. This technique is advantageously employed when small changes in direction and inclination are to be detected or measured. It is very well suited for precise alignment.

### 2.3.2 Theodolite Stand

The theodolite is mounted on a pedestal which provides high rigidity and stability, it is permanently fixed to the rails. Raising and lowering of the instrument mount provides for a coarse vertical ($x_T$) adjustment. The stand is also equipped with two additional devices for precise vertical ($x_T$) and lateral ($y_T$) adjustment, a high precision lift and a precision slide which will be briefly described below.

A photograph of the theodolite stand is shown in Figure 5. This photo shows the Zeiss ETh 2 electronic theodolite in its position, ready for alignment. The I-beam structure that supports the rails is extended beyond the end of the chamber, and supports the theodolite on a rigid stand. The stand is geared to facilitate height adjustment. At the top of the (shiny) post is a high precision lift, followed by a precision slide for lateral adjustment of the position of the theodolite. On top of that rests a levelling stage which is used to level the theodolite prior the commencement of the alignment. Through the rectangular opening into the chamber, the AL-560 AUT roll positioner can be seen.

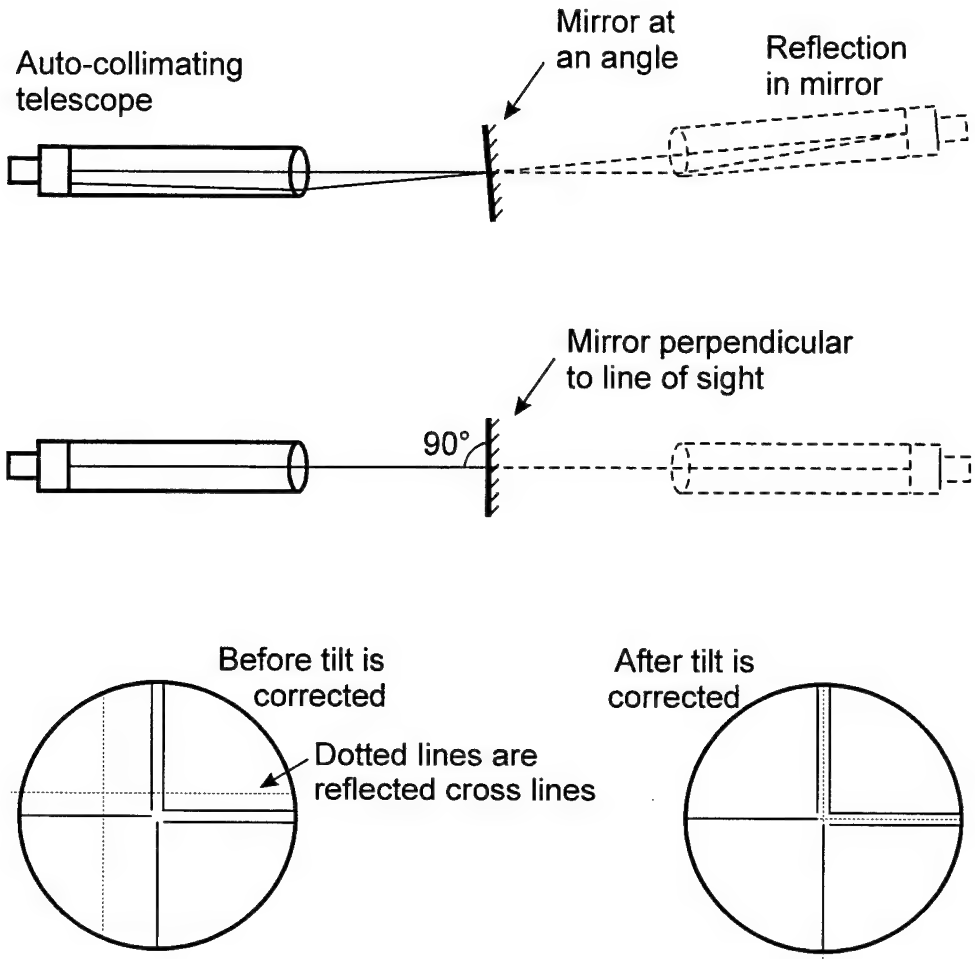



Figure 4 - Autocollimating: The Line of Sight and it's Reflection. [3]

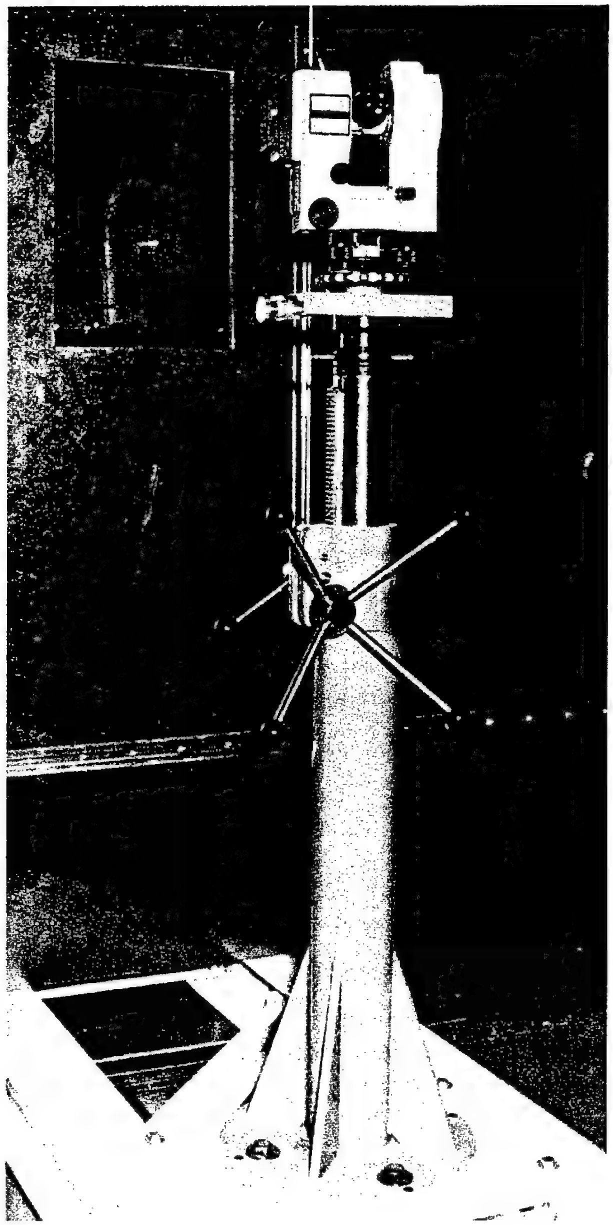


Figure 5 - Theodolite Stand

The high precision lift provides precisely controlled vertical ($x_T$) displacement through a 16 mm range. Smooth, fine screw action makes minute height adjustments of previously levelled instruments, fast and easy, by minimizing the need to re-level the instrument.

The precision slide has precision roller bearings which permit accurate ($y_T$) translation of a precision plumbed instrument minimizing the need for readjustment. The slide has a substantial 50 mm travel for horizontal transversal displacement. The platform seats into the precision lift to allow convenient slide positioning of the theodolite mounted on it.

### 2.3.3 Two-way Spindle Target Mirror Assembly

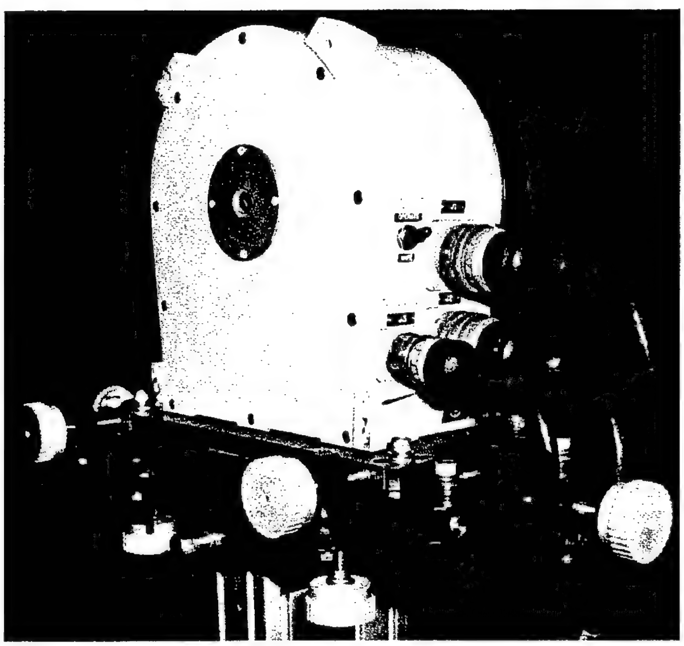
The Brunson spindle target mirror assembly designed to be magnetically attached to the end of a shaft of a spindle, is attached to an antenna positioner platen at its centre and is used as the autocollimation mirror as mentioned above in the theodolite section. True rotational centerline may be referenced quickly and accurately with the mirror assembly. The original mirror has both a 100% reflective surface and a multiple filar bi-filar target. Translation adjustments are provided to set the target concentric to the centre of rotation, while angular adjustments set the mirror precisely normal to the positioner axis of rotation. The mirror mounting plate has four fine-threaded displacement screws knobs, two opposing in each direction with a range of approximately 10 mm. Angular motion is controlled by three adjusting screws 120° apart. By setting an optical instrument to the mirror, precise extension of the positioner rotational axis is ensured.

The mirror assembly is described as "two-way" because it has a thru hole in the centre, and consequently, the mirror is visible when looking through the back of the assembly. As the positioners also have a centre thru-hole for the passage of the RF cable, the back of the mirror can also be seen through the hole. This capability is a very important feature of the alignment method, and it is used with great advantage when the original mirror, furnished with the assembly, is replaced by a special target mirror, described below, to check for and adjust the intersection of the azimuth axis with the roll axis.

Photographs in Figure 6 and 7, show two identical mirror assemblies mounted on the AL-360 and AL-560 positioner's platens. Because they were mounted on the positioners, the thru-holes of the positioners are not visible in the front views. The mirror assembly adjustment screws have large knobs fixed on them for precise adjustment. As mentioned above, the three knobs facing the front are for adjusting the angle of the mirror, while the four pointing radially outward are for adjusting the position of the centre of the target in the holder. The large black circular disks on the front view photos are the platens which are rotated by the positioners. The photo in Figure 7 b) shows the rear view of the AL-560 positioner. The thru-hole is clearly visible. It is through this hole that the back of the mirror is viewed during the optical alignment.

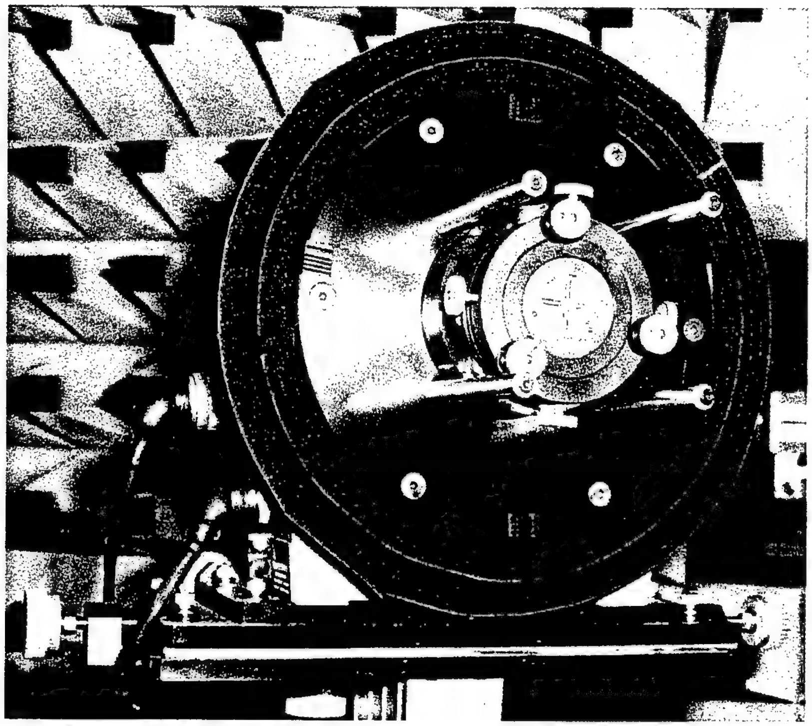
The original mirror in the mirror assembly had a dark target deposited on top of the mirror coating making the target visible only from one side. This situation was very unfortunate, because, it made the assessment of the intersection of the positioner axes more difficult. Therefore, a special target mirror, illustrated in Figure 8, was designed at DREO by the author and then fabricated under contract by the original manufacturer. The exact dimensions and type of mirror

a) Front view

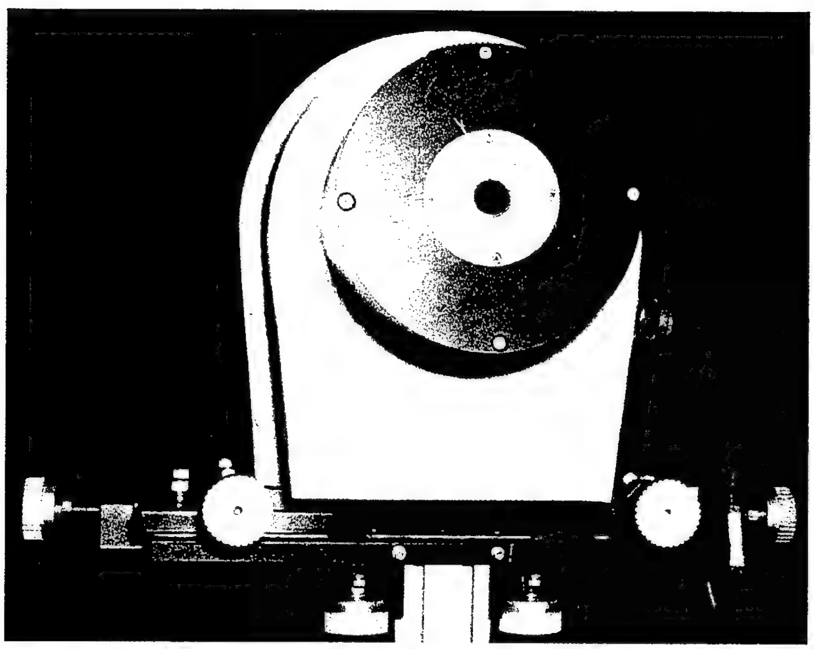


b) Rear view

Figure 6 - View of the AL-360 Positioner with the Probe Alignment Fixture and the Mirror Assembly.



a) Front view



b) Rear view

Figure 7 - View of the AL-560 Positioner with the Roll Alignment Fixture and the Mirror Assembly.

were specified. The line width, line separation of each bi-filar line set of the target were specified as well.

The mirror characteristics are listed below:

i. circular mirror with a clear target etched in the single reflective coating on the top of the mirror face;
   - the reflective coating is protected aluminium ($AL/SiO_2$) deposited for a minimum optical density of 3.0 (T=0.1%);
   - an anti-reflection coating is deposited on the other face;

ii. the glass substrate is a circular optical flat made from Quartz or Zerodur with the following characteristics:
   - both faces are parallel within 1 to 2 arc sec. and;
   - flat to at least one quarter wavelength of sodium light;
   - the refraction index of the glass must be as small as possible, ideally below 2;
   - the dimensions are 1.5" OD ± .01" with a thickness of 0.19", which is the size of the original mirror;

iii. the target is a multiple filar/bi-filar target similar to the original target, but two circles, a fine-line partial cross and a square centre dot, were added to complement the target.

Table 1. below lists the target dimensions.

| Line Set | Line Separation mm | Line Width mm | Line Length mm |
|---|---|---|---|
| 1 (Bi-filar) | 2.8 | 0.5 | 16 |
| 2 (Bi-filar) | 0.9 | 0.3 | 2 |
| 3 (Bi-filar) | 0.3 | 0.1 | 0.6 |
| 4 (Single) | | 0.1 | 14.5 |
| 5 (Circle) | | 0.2 | 5 (dia.) |
| 6 (Circle) | | 0.2 | 15 (dia.) |
| 7 (Centre Square dot) | | 0.1 | 0.1 |

**Table 1. - Target Specification**

### 2.3.4 Positioner Alignment Fixture

The positioner alignment fixture is an assembly of three metal plates designed to be installed under the AL-360 and the AL-560 positioners. It is fitted with adjustment knobs to give 3 degrees of freedom of adjustment. With this fixture, a positioner can be aligned in azimuth (yaw, $\beta$), elevation (pitch, $\alpha$) and can be displaced laterally in the transverse (y) direction. The top plate

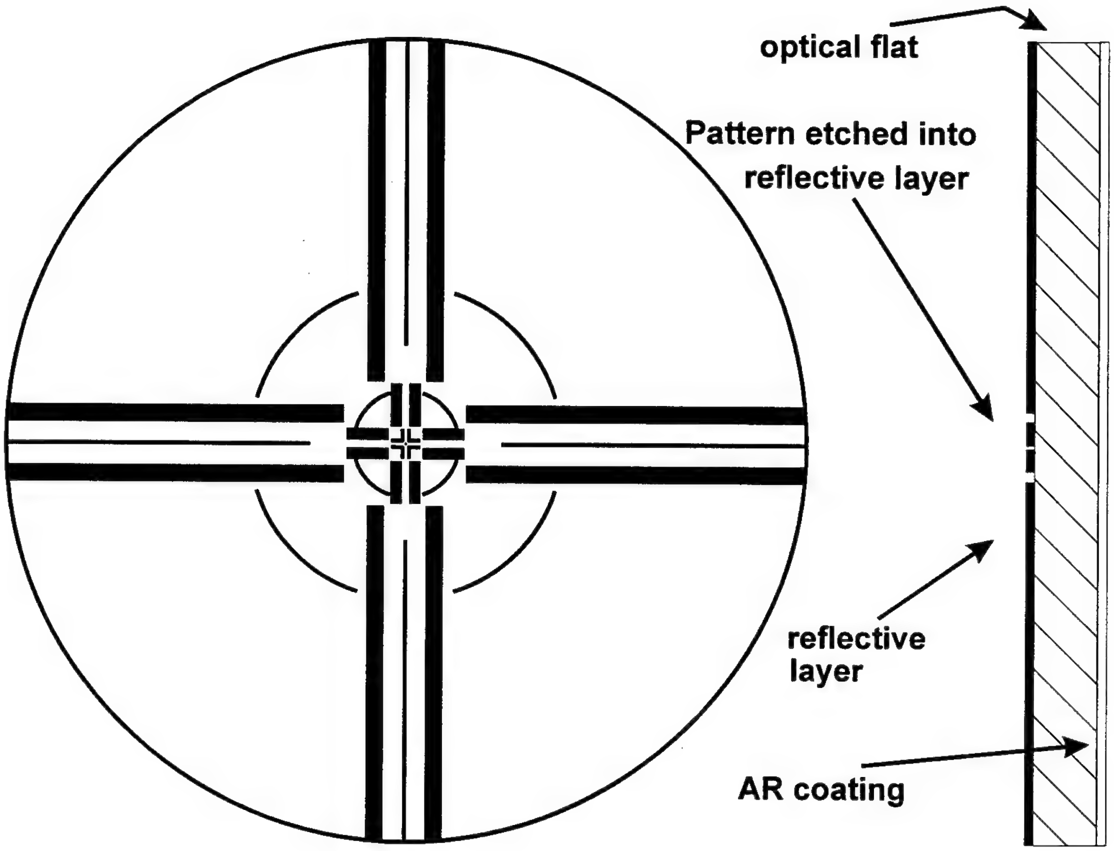



Figure 8 - Target Mirror

is attached under the base of the positioner and the bottom plate to the vertical mast. The middle plate is sandwiched between these two and held in place by bolts which are tightened during alignment.

The top plate has a centre axle and can rotate around the middle one by the action of the two azimuth knobs. This give an azimuth alignment (or yaw) capability to the positioner. The azimuth travel range is ± 3°. The middle plate can pivot around the front end of the bottom plate to adjust the positioner in elevation (or pitch). The elevation travel range is ± 1.5°. As well, the middle plate can move laterally to translate the positioner in the transverse (y) direction. The lateral travel range is ± 10 mm.

Before initiating these multiple adjustments, the attachment bolts are released slightly to allow some movement of the plates. The adjustment knobs are then rotated in the proper directions to perform the alignment required and when the adjustment is very close, the attachment bolts are tightened and the knobs are readjusted and re-tighten to compress the metal parts and correct for any alignment error due to metal elasticity and slack of the screws.

Figures 6 and 7 again show how the probe and roll positioners are mounted on the top of the alignment fixtures. The 3 black plates described above can be identified easily and the attachment bolts holding them together as well. Four bolts attach the top plate to the middle plate and four additional ones attach the middle plate to the bottom one. The fixture and the adjustment knobs are shown best in the rear views of the positioners. The knobs pointing toward the rear facilitate adjusting the yaw of the positioner, the ones pointing toward the floor are for the pitch, and those pointing out to the side are for lateral positioning. Under the plates, in Figure 6, one can see the vertical adjustment fixture which uses sliding wedges for the AL-360 positioner vertical translation. The steel bolt pointing toward the back is used to adjust the vertical adjustment fixture. In the front views, four steel rods can be seen which are used to support the plate on which the antenna is to be mounted.

# 3 - Methodologies and Common Operations

## 3.1 Introduction

The method of optical alignment is accomplished through several procedures and techniques using levels, the theodolite and the two-way spindle target mirror assembly. Levels are required to align the vertical axis of the azimuth positioner. The mirror assembly is a very important and efficient device, used to optically define an axis of rotation among others. The purpose of aligning the horizontal-axis positioners, such as the roll and the probe positioners, is to orient their rotational axes to be horizontal, normal to gravity, and coincident. Their axes must also intersect the azimuth positioner axis and be orthogonal to it. The mirror assembly is the best tool for that purpose, because its mirror can be set up normal to the axis of rotation and its target made coincident with the axis. So when the mirror is aligned to the positioner, it becomes easy to move the positioner to point in a specific direction using the alignment device(s) and the theodolite for guidance.

Some of these procedures and optical techniques are used only once during the alignment process, such as the determination of the direction of the rails or the vertical orientation of the azimuth axis. Others, on the contrary, are more common and are reused a few times, such as the installation of the mirror assembly on an axis, the setting of an axis parallel to another, or the coincidence of those axes. In this section, all methods, procedures or common operations will be described in detail. The following alignment procedures are listed below:

i. alignment of the optical axis parallel to the support rails direction (section 3.2);

ii. alignment of the azimuth axis parallel to gravity (section 3.3);

iii. installation of the mirror assembly, alignment of the mirror normal to an axis and determination of a rotation axis (section 3.4);

iv. alignment of a rotation axis parallel to the theodolite axis (section 3.5);

v. alignment of a rotation axis coincident with the theodolite axis (section 3.6);

vi. methods for axes alignment (section 3.7).

## 3.2 Alignment of the Optical Axis Parallel to the Support Rails Direction

This procedure consist in finding the rails direction and aligning the optical axis on a plane perpendicular (vertically) to the rails. This plane is also parallel to them and approximately midway between them. Gravity must be in the plane and its direction known accurately. Two procedures are described: the telescopic method and the Autocollimation method.

### 3.2.1 The Telescopic Method

The telescopic method is a procedure performed, referring to Figure 9, with the following steps:

i. the telescope of the theodolite is focused on a reference point on the probe positioner located at position A on the rails;

ii. the carriage is moved forward on the rails a distance $d_1$ from position A to position B. The distance $d_2$ from position B to the theodolite is measured;

iii. the theodolite is again focussed on the reference point on the probe positioner and, is moved laterally a distance $s_1$ from point A to point B without changing the pointing angle until the reference point on the positioner is visible again in the eyepiece and centred on the cross-hairs as in (I). The telescope is refocussed;

iv. the theodolite is translated to point C at a distance, $s_2 = s_1 d_2 / d_1$, from point B. The telescope is then re-aligned to the reference point and this new direction of the optical axis constitutes the direction of the rails;

v. the carriage is moved back to position A. If the reference point is still centred on the cross-hairs after the telescope is refocused, the theodolite points in the direction of the rails. If not, the process is repeated;

### 3.2.2 The Autocollimation Method

It should be noted that to align the optical axis of the theodolite to the direction of the rails, it is only necessary to use an optical target, as just described above, and focus on it at each end of the carriage travel. If, however, one is willing to use an Autocollimation mirror and align it normal to the optical axis (or line of sight) and autocollimate, it will be possible to determine if the direction of the rails is constant over the range of travel of the carriage. If the autocollimation remains valid during the carriage travel, then the rails are straight. The steps below are described for the autocollimation option.

This procedure is performed referring to Figure 9 and requires the following steps:

i. mount the spindle target (autocollimation) mirror assembly on the AL-360 probe positioner platen, set up the theodolite and turn on the autocollimation cross;

ii. mark the position along the rails that the carriage supporting the AL-360 will be at during antenna measurements. This is important, as it will be necessary to return to this position during and following this alignment procedure. This is position A in Figure 9. Mark also the position that the carriage will be at following the movement requested in paragraph v (below). This is position B in Figure 9;

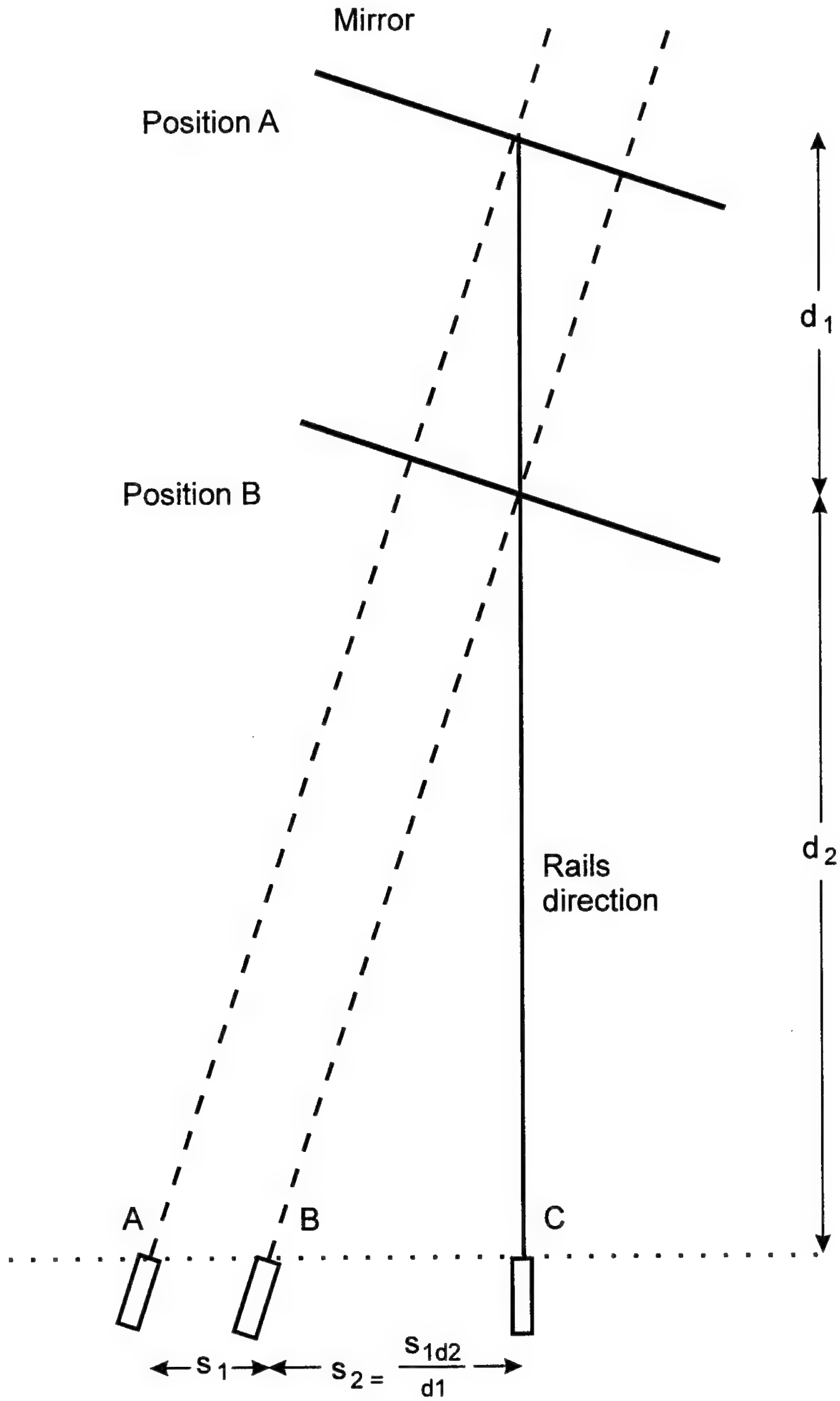



Figure 9 - Rails Alignment

iii. position the theodolite such that the target on the mirror is coincident with the black reticule of the telescope (focussed on the mirror);

iv. adjust the mirror for autocollimation at position A, i.e. the theodolite and mirror are aligned so that the optical axis is parallel to the normal to the mirror. This condition is satisfied when the light beam from the theodolite in autocollimation mode (focussed at infinity) is reflected back from the mirror to the theodolite (visible as a "lit cross") and this lit cross and the black cross-hairs of the telescope are coincident. This is explained in section 2.3.1;

v. move the target/mirror (probe tower carriage) along the rails to some new position B and measure the distance of travel $d_1$ and the distance to the theodolite $d_2$. If the line of sight of the theodolite (focussed on the target) is not parallel to the rails, the target on the mirror will have moved. Also, if the system is still autocollimated (theodolite focussed at infinity), the angle (yaw) of the rails will not have changed;

vi. move the theodolite (focussed on the target) without changing the (azimuth) angle (i.e. with linear translation only) until the black cross-hairs are once again lined up on the target. Measure the magnitude of this movement (from A to B), $s_1$;

vii. calculate the amount that the theodolite would have to move, $s_2 = s_1 d_2 / d_1$, so that it would be on the axis of the rails. Move it there (from B to C). Adjust the direction of theodolite (focussed on target) so that it is pointing at the mirror. Re-adjust the mirror for autocollimation by adjusting the angular position of the mirror (theodolite focussed at infinity). This will allow reconfirmation of the autocollimation when the carriage is returned to its starting point;

viii. move the carriage back to its starting point and verify that the target position has not changed. If it has remained stationary, then the theodolite is pointed parallel to the rails. If not, repeat the process until it is so. It may be that the rails are not straight; if this so, then further improvement in the determination of the direction of the rails may not be possible.

## 3.3 Alignment of the Azimuth Axis Parallel to Gravity

The azimuth axis (AL-860 axis) must be adjusted vertical or parallel to gravity. This alignment is done with levels placed on the positioner platen. The level may not be seen to be a precise instrument but some levels can provide error bounds or even angles. Although the platen is a convenient surface, it must be remembered that the important parameter is the axis about which the positioner rotates the platen. To measure or align the axis, it is necessary to adjust the axis orientation until the level on the platen does not move as the axis is rotated through 360°. It should be noted that the surface of the platen may be neither flat nor perpendicular to the axis, but does not need to be for the alignment of the axis, this is illustrated in Figure 10.

One method of alignment using levels consists of placing two levels (or three if available) that are 120° in rotation apart on the platen between the positioner support jacks and adjusting the support feet so that all levels are reading level, keeping in mind what was discussed in the previous

paragraph about the flatness and relative orientation of the platen in relation to the axis. Another method using only one level is described below and illustrated in Figures 10 and 11.

The procedure to align the azimuth axis with one level is as follows:

i. the azimuth turntable is rotated in equal increments and stopped at the end of each increment, at which time, the level is read;

ii. the rotation continues and data are recorded for 360°;

iii. the tabulated values are plotted with azimuth angles as the abscissa and the level reading as the ordinate.

Figure 11 shows a graphic generated using this method. The degree and direction of axis inclination can be determined by an analysis of the results of the measurements. A perfectly vertical axis would yield an identical level reading for any arbitrary position. If the platen is not level, the angles will plot as a sine wave with one cycle equal to 360° of azimuth. The peak-to-peak deviation will be twice the positioner axis tilt or inclination, and the average will be the tilt of the level. Level tilt would occur if the platen surface is not level and also not perpendicular to the axis of rotation. To correct for axis tilt, the platen is rotated to the angle where the tilt is maximum. The support feet of the positioners are adjusted to decrease the tilt until the level reading reaches the tilt of the level value. Repetition of these steps might be required, but as the axis is more accurately aligned, the amplitude of the sine wave will diminish and the level reading will not change any more as the axis is rotated. This will ensure that the AL-860 axis is straight up and down and that it is adjusted parallel to gravity.

## 3.4 Installation of the Mirror Assembly, Alignment of the Mirror Normal to An Axis and Determination of A Rotation Axis

To set the target mirror [5] coincident to the axis, the principle of noting the deviation from perfect alignment is utilized. The mirror assembly is placed on the turntable as close as possible to the centre of rotation and normal to the axis (section 3.4.1). The theodolite is placed such that it is autocollimated with the mirror. The axis is rotated 180° and the required movement of the theodolite to reacquire azimuth and vertical autocollimation is measured. The theodolite is moved to the centre of these two readings and the mirror is readjusted to autocollimation. Repetition of these steps may be required. At this point the mirror face is normal to the axis of rotation (section 3.4.2). The theodolite is then focussed on the mirror target and similar steps are repeated to place the centre of the target on the axis of rotation (section 3.4.3). It is not necessary that the theodolite be referenced to the axis to perform the mirror alignment. Depending on the type of alignment performed, the positioner axis or the optical axis of the theodolite are aligned coincident to the other axis using these same principles by adjusting the theodolite or positioner until the theodolite cross-hairs are simultaneously aligned with the target and autocollimated.

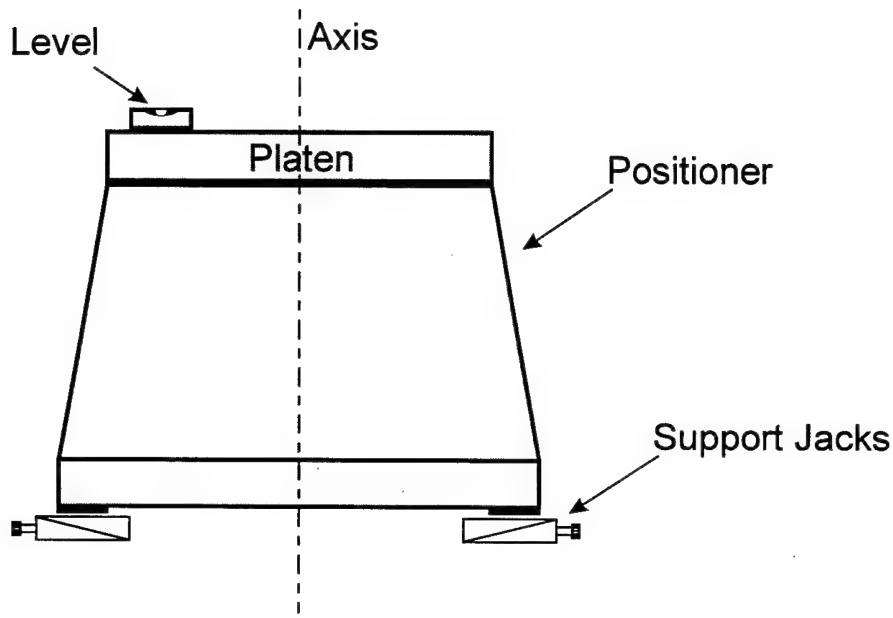



Figure 10 - Alignment of the Azimuth Positioner Using a Level

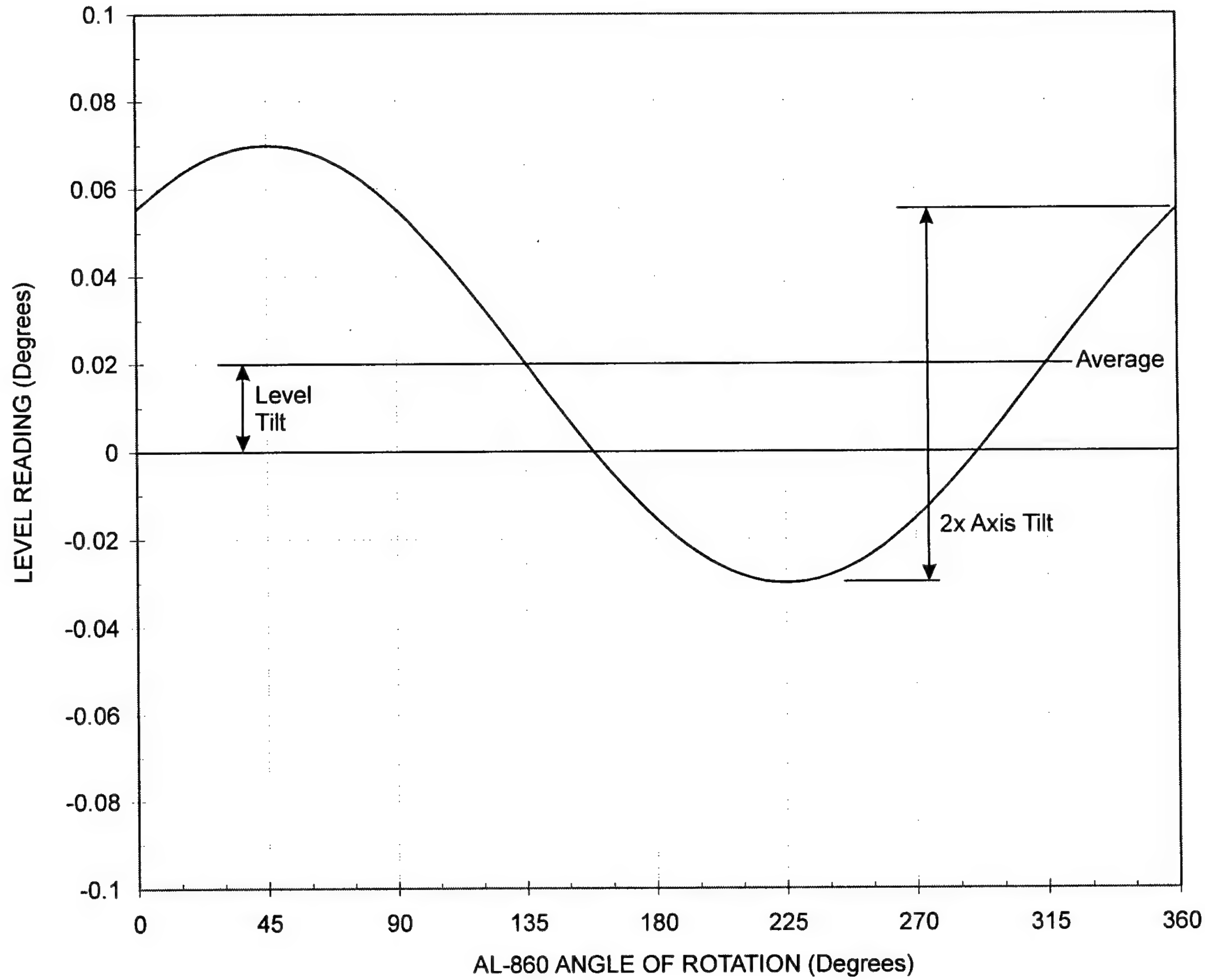



Figure 11 - Inclination of Azimuth Axis

The alignment of the mirror assembly [5] involves its installation on the positioner platen and two separate adjustments: orthogonality of the mirror face with the axis of rotation and intersection of the rotation axis with the centre of the mirror target face.

## 3.4.1 Mirror Assembly Installation

The mirror assembly installation procedure consists of pre-aligning the mirror in its carrying assembly and orienting the axis of rotation to permit the autocollimation alignment process to be performed effortlessly.

### 3.4.1.1 Mirror Preparation

The mirror preparation is done by performing the following steps:

i. the target of the mirror is manually centred on the spindle mirror assembly;

ii. the target cross is aligned with the four linear adjustment screws to facilitate later adjustment;

iii. the angular adjustment screws are adjusted with an equal displacement to put the mirror closer to its final position;

iv. the mirror is checked to be sure that it is secure and tight in its holding plate so that its orientation in relation of the assembly does not change during adjustment;

v. the mirror assembly is placed on the turntable approximately on the rotation axis and the assembly is rotated until opposite translating adjusting screws define horizontal and vertical lines.

The mirror preparation is an important step for the alignment process because, when using autocollimation, the bright light must be reflected back to the telescope. The mirror thus must be pre-aligned fairly close to its final adjustment and also the positioner axis of rotation must be almost parallel to the optical axis. If it is not the case, the light will be reflected away from the theodolite and no alignment will be possible because it will not be possible to see the reflection from the target mirror when looking through the telescope.

### 3.4.1.2 Mirror Orientation

The following approach could be used to remedy the situation just described:

i. the theodolite is focussed on the telescope objective i.e. the focus distance is twice the distance between the theodolite and the mirror. Looking into the eyepiece at the telescope or with the naked eye just beside the telescope, and aiming directly at the mirror, one could find where objects close to the theodolite are reflected back;

ii. if the telescope objective cannot be seen in the eyepiece, it means that the mirror and/or the positioner axis are not adequately oriented. Spin the positioner, and by so, the mirror, and

observe the objects reflected by the rotating mirror. They will trace a circle which may be fairly wide. The radius of that circle is proportional to the angle between the normal to the mirror and the positioner axis of rotation;

iii. determine the position of the centre of that circle of rotation where the positioner axis points;

iv. adjust the angular adjustment knobs of the positioner alignment device to move the centre of the circle toward the theodolite optical axis, thus bringing the full circle described by the target centre into view in the telescope;

v. if required, because the size of the circle depends of the mirror orientation with respect to the positioner axis, stop the positioner rotation and adjust the mirror tilt adjustment screws to decrease the diameter of the circle;

vi repeat the above steps until the circle is visible in the telescope;

vii spin the positioner, set the theodolite for autocollimation and adjust again the positioner orientation so that the lit cross is visible in the eyepiece for a complete rotation.

A more precise adjustment will be done later in performing the procedure to set the mirror normal to the positioner axis and to align the axis parallel to the optical axis.

### 3.4.2 Adjustment of the Spindle Target Mirror Normal to the Axis of Rotation

The procedure to adjust the mirror face normal to the rotation axis is as follows [5]:

i. place the mirror assembly on the positioner platen and pre-align the mirror as described in the previous paragraph;

ii. adjust the theodolite to autocollimation, i.e. set the theodolite until the lit cross and the telescope reticule are juxtaposed and record the azimuth and vertical readings on the theodolite;

iii. rotate the axis 180°, readjust the theodolite to autocollimation and record the theodolite readings;

iv. determine the midpoint between each pair of azimuth and vertical readings, and mechanically set the theodolite to that value;

v. adjust the mirror using the tilt adjustment screws until the theodolite is autocollimated;

vi. repeat the above steps until the variation is within a few seconds of arc or minimal.

At this point, the mirror face is normal to the rotation axis. This can be verified by spinning the axis and observing the autocollimation bright light movement in the telescope. If the theodolite stays in autocollimation for a full rotation, i.e. the lit cross is superposed over the black

cross-hairs, the mirror face is normal to the rotation axis. In other words, the mirror axis is parallel to the positioner axis.

A program for the HP-42S calculator has been developed by the author to calculate, among other parameters, the midpoint values between each pair of data readings. A description of the program including theory of operation, user instructions and a listing can be found in Appendix A.

### 3.4.3 Alignment of the Target to Intersect the Axis of Rotation

The procedure to set the target on the mirror concentric to the positioner axis of rotation is described in the following steps:

i. rotate the axis until opposite translation adjusting screws define horizontal and vertical lines;

ii. using the theodolite as a telescope, i.e. focussed on the mirror target, align the target in the theodolite cross-hairs and record the azimuth and vertical readings of the theodolite;

iii. rotate the axis 180°, readjust the theodolite to align with the target and record the theodolite readings;

iv. determine the midpoint between each pair of azimuth and vertical readings, and mechanically set the theodolite to that value. The calculator program may be used with advantages for this calculation;

v. adjust the mirror position using the translation adjustment screws until the target is centred on the reticule of the theodolite;

vi repeat the above steps until the variation is very small.

At this point, the centre of the target is coincident to and intersects the rotational axis. This situation can be verified by spinning the axis and observing with the telescope that the centre of the target is stable and does not move in a circle around the reticule during the rotation, but that the target is concentric to the centre of rotation.

## 3.5 Alignment of a Rotation Axis Parallel to the Theodolite Axis

The procedure to adjust a positioner axis to be parallel to the optical axis is as follows:

i. adjust the theodolite to autocollimate the mirror (previously adjusted normal to the axis). It should be noted that to make this adjustment, the target on the mirror does not need yet to be coincident with the rotational axis. In autocollimation, only angles are seen and measured; the target cannot be seen as the theodolite is focussed to infinity. Only the axis orientation is important;

ii. set the theodolite line of sight orientation to 0° azimuth and to 0° vertical. This sets the optical axis to horizontal, in the direction of the rails and, if the two axis are not parallel, will move the lit cross away from the telescope cross-hairs;

iii. adjust the positioner axis orientation until the theodolite returns to autocollimation when the lit cross will be superimposed on the telescope cross-hairs. This is done by rotating the pitch and yaw adjustment knobs of the positioner alignment device.

When the lit cross coincides with the theodolite reticule, the normal to the mirror is parallel to the optical axis of the theodolite, and therefore the positioner axis is parallel to the optical axis. At this point, both axis are parallel but they do not yet coincide. The following procedure below describes how to make them coincident.

## 3.6 Alignment of A Rotation Axis Coincident with the Theodolite Axis

This adjustment is done after the positioner axis is set parallel to the optical axis and after the mirror target is set concentric to the centre of rotation. The procedure is as follows:

i. verify that the optical axis of the theodolite, or line of sight, is set to 0° azimuth and to 0° vertical;

ii. focus the theodolite on the mirror and linearly translate the position of the theodolite or the position of the positioner so that the theodolite cross-hairs coincide with the target centre, i.e.; or

iii. if the theodolite axis must be made coincident with the positioner axis, lateral and vertical offset of the theodolite position is done using the two precision linear translation stages on the theodolite stand;

iv. if, on the other hand, the AL-360 positioner axis must be made coincident to the optical axis, the linear transverse translation stage of the positioner alignment device is adjusted. The vertical stage as well is adjusted if required. In the case of the AL-560, there is no vertical adjustment stage. The vertical height of the AL-560 is a reference for the range axis height, so if vertical adjustment is required, the vertical translation stage of the theodolite stand is adjusted.

## 3.7 Methods for Axes Alignment

At the end of the procedure, at paragraph 3.4.1.2 step vii, in the mirror installation section, where it is described how to pre-orient the autocollimation mirror and the positioner axis toward the theodolite, the positioner is spun and the autocollimation bright cross behaviour is observed through the eyepiece. If the circle, that the bright cross described, is fully visible in the eye-piece, it is not necessary to refine the mirror alignment. Two methods are described below to

align the axes to be parallel to each other. In the spinning method, adjustments are made while the positioner is still spinning. In the static method, the positioner is stopped at two points on its revolution and the relevant adjustment is calculated.

When the mirror on the rotating platform is sighted in autocollimation mode, the lit cross will inscribe a (yellow) circle of some diameter "$\alpha$" with its centre some distance "$\beta$" away from the centre of the theodolite reticule, as illustrated in Figure 12. The radius of the circle, angle "$\alpha$", is a function of the degree of misalignment between the mirror axis and the positioner axis. Similarly, the angular distance "$\beta$", between the centre of the circle and the theodolite reticule, is also a function of the degree of misalignment, but between the positioner axis and the optical axis.

As the purpose of this exercise is to align both the positioner and the theodolite axes parallel to each other (and not to align the mirror axis normal to the positioner axis), it is only necessary to adjust the positioner pitch and yaw controls to bring the centre of the yellow circle over the centre of the reticule, without having to reduce the diameter of the yellow circle by precisely orienting the mirror axis normal to the rotation axis. Two alternate methods are available for that purpose. With the spinning method, the yellow circle is centred while the positioner is spinning, while with the static method, the coordinates of the positions of two points on the circle, that are nearly diametrically opposite, are measured and are used to calculate the movement of the positioner required to centre the circle.

### 3.7.1 Spinning Method

The procedure for the spinning method is done referring to Figure 12 a) and executed with the following steps:

i. spin the positioner, set the theodolite for autocollimation. The mirror is already pre-aligned as described in the mirror installation section. The lit cross as seen in the telescope moves in a circle with the positioner rotation, step 1 in the graph. The bright light circle is yellow in colour;

ii. if the yellow circle is too large in size, it might be difficult to determine the position of the circle centre by eye. In that case, the positioner could be stopped and the circle diameter reduced to a more manageable size via the mirror tilt adjustment screws, corresponding to step 2 in the graph. This will move the plane of the mirror closer to be normal to the positioner axis, which will be the case only when the circle size is reduced to a point;

iii. after this, while the positioner is spinning, the pitch and yaw controls on the positioner alignment device are adjusted to bring the "now smaller" circle to overlap the theodolite reticule, step 3 in the graph.

Both axes, the rotation axis and the optical axis, are parallel when the yellow circle is centred over the theodolite cross-hairs, however this assessment of parallelism is subject to the precision and precaution used by the theodolite operator in determining the position of the centre of

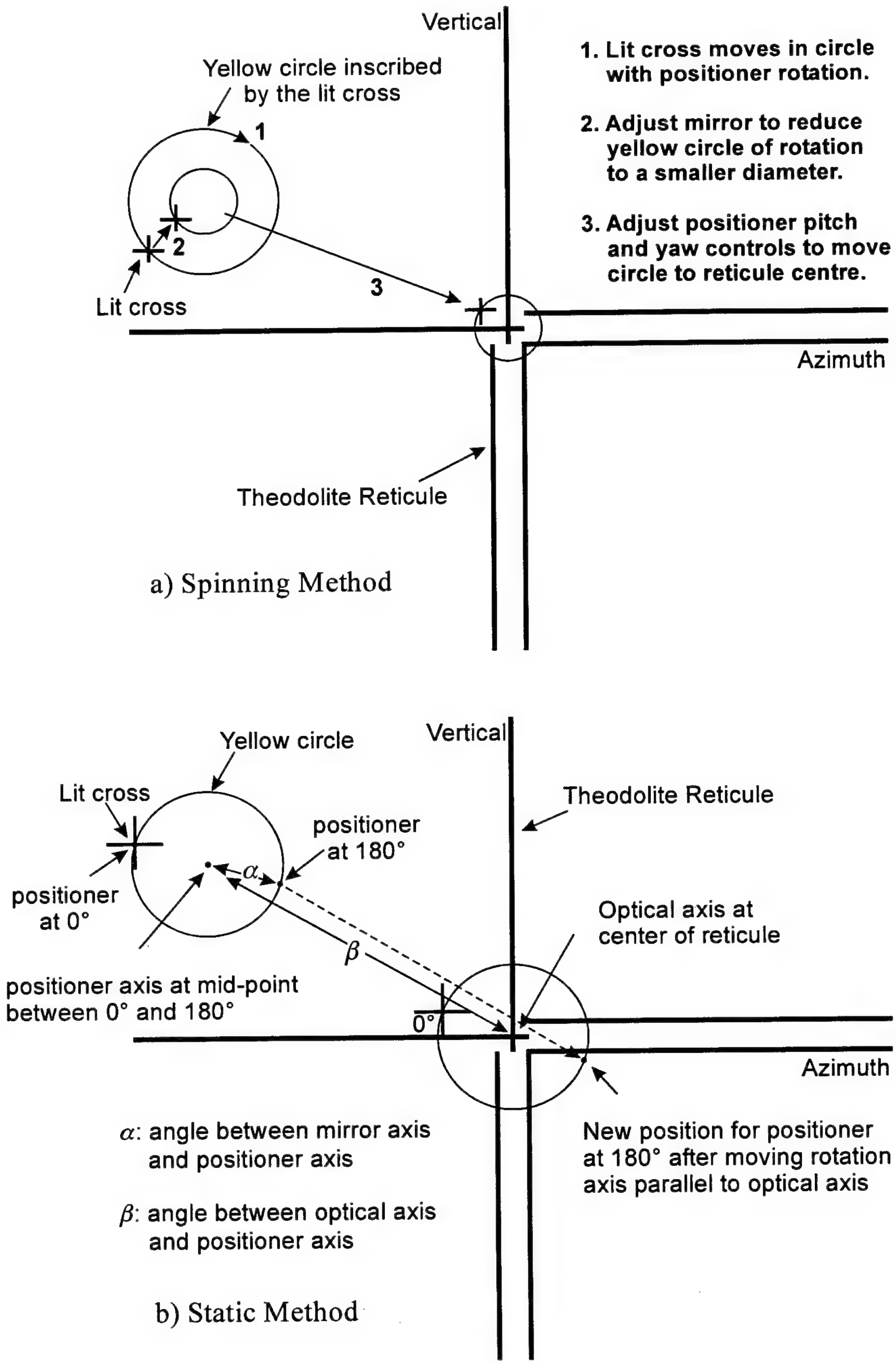



Figure 12 - Alignment of Rotating Mirror and Positioner Axis Using Autocollimation

the yellow circle. For a more accurate assessment and alignment of the axis, the yellow circle must still be reduced to a point or almost so. It is, however, a necessity when the wobble of the rotation axis is to be measured.

### 3.7.2 Static Method

In the static method, the theodolite is set for autocollimation and the positioner is rotated to two positions 180° apart, at angle 0° and angle 180° of rotation. Readings are taken and the midpoint calculated. The midpoint between these two points represents the coordinates of the yellow circle as introduced in the previous paragraph. It is also the angular distance "β" between the positioner axis and the optical axis (at the centre of the reticule), as shown in Figure 12 b). The distance "β" is then subtracted from the readings at 180° to determine the new position at 180° attained after the axis is moved to orient both axes parallel. The theodolite is then moved to this new calculated (azimuth and vertical) position. The positioner stays at 180° and the pitch and yaw controls are adjusted until autocollimation is reached again. If the adjustments are done correctly the new midpoint coordinate should be 0° azimuth and 0° vertical. Repetition of the procedure might be required.

The procedure for the static method is performed referring to Figure 12 b) and executed with the following steps:

i. set the theodolite in autocollimation mode with the mirror assembly pre-aligned as described previously in mirror preparation section 3.4.1.1 and rotate the positioner to angle 0°.

ii. record the azimuth and vertical readings on the theodolite;

iii. Rotate the axis to 180°, readjust the theodolite for autocollimation and record the theodolite readings;

iv. Determine the midpoint between each pair of azimuth and vertical readings, subtract these two values from the 180° readings and set the theodolite to that value;

v. Leaving the positioner at 180°, adjust the pitch and yaw controls of the positioner alignment device until the theodolite is autocollimated.

vi. Repeat the previous steps until the midpoint is at 0° azimuth and 0° vertical, i.e. until the axis of rotation is parallel to the optical axis.

This procedure is easily made using the calculator program which gives directly the new theodolite angular position for the positioner at 180°. The above steps are repeated until the variation is within a few seconds of arc.

# 4 - Alignment Procedures for the Spherical Antenna Measurement System

## 4.1 Introduction

In the previous sections, the description of the spherical system elaborated on the positioner configuration, the various devices and tools required for the optical alignment, and on the numerous degrees of freedom available for the adjustments required to carry out this alignment. In addition, the methodologies and common alignment operations were also described in detail.

In this section, the implementation method for the complete alignment procedure will be presented. When a detailed procedure for a typical positioner, mirror alignment or other function is required, reference to such operation described in chapter 3 will be given. Several references to the alignment degrees of freedom are often given in the following paragraphs. Please refer to Figure 2 and to paragraph 2.2 in these instances to recall their meanings. However, before starting the description of the alignment procedures, the initial installation of the AL-860 azimuth positioner and of the AL-560 roll positioner will be described first.

## 4.2 Azimuth Positioner Initial installation

### 4.2.1 Introduction

Before describing the optical alignment procedures as such, it is important to discuss the initial installation of the AL-860 azimuth positioner over its support carriage. If this installation is not done accurately and with great precision before attempting the optical alignment of the spherical positioner system, it may be impossible to adjust the height of the AL-360 axis during the alignment exercise. The reason for this is that the vertical adjustment fixture for the AL-360 permits only a vertical translation range of about 1.9 mm, whereas the three leveller fixtures under the feet of the AL-860 have each a range of 10 mm of adjustment. That is why it is imperative that the AL-860 be pre-aligned at initial installation time so that the axes of the AL-360 and of the AL-560 positioners be at approximately the same height. It is intended that, at optical alignment time, the AL-360 vertical adjustment stage will be used only to perform a fine adjustment correction.

### 4.2.2 Procedure for the Azimuth Positioner Initial installation

This procedure is done after all the three positioners are mounted on their support carriage and posts and configured as illustrated in Figure 1. The Al-860 mày not be levelled yet or its rotation axis oriented vertical, but this will be done during the execution of this pre-alignment exercise. This procedure will list all the steps required for the initial installation of the AL-860.

The target mirrors are mounted on the AL-360 and the AL-560 platens and the targets centred on their respective rotation axis. The AL-860 axis is aligned vertical and its support jacks are adjusted so that the height of the AL-560 axis coincides with the height of the AL-360 axis. The

theodolite is used to establish this coincidence. The theodolite, with its line of sight horizontal, oriented toward the AL-360 and focused on the mirror, is adjusted vertically until the cross-hairs are concentric with the target on the mirror. It is then oriented toward the AL-560 and refocussed on the mirror assembly mounted on its platen. The cross-hairs and the target on the AL-560 are observed in the theodolite objective and the AL-860 height is adjusted until the cross-hairs become concentric with the target. This height adjustment is performed by raising or lowering equally the three support jacks under its base. All these adjustments must be executed while preserving the vertical orientation of the AL-860 axis. This procedure will normally be accomplished only once (i.e. at the initial installation of the positioners).

The steps required to adjust the support feet of the AL-860 positioner are as follows:

i. set the adjustment of the vertical translation stage of the AL-360 to its mid-position;

ii. install the spindle target mirror on the AL-360 platen and adjust the target to intersect the axis of rotation. The procedure to set the target on the mirror concentric to the centre of rotation is described in section 3.4.3;

iii. Make a visual check or use a level to verify the positioner axis is almost horizontal;

iv. orient the theodolite toward the AL-360, adjust the line of sight to be horizontal (i.e. with a vertical reading of 0°) and focus on the mirror;

v. adjust the theodolite vertical adjustment stages, located on the theodolite stand, so that the cross-hairs coincide with the target. At this point, the line of sight of the theodolite is at the same height as the AL-360 axis (at the platen), or in other words, the line of sight of the theodolite crosses or meets the positioner rotation axis at the platen;

vi. adjust the AL-860 axis to be vertical using levels by following the adjustment steps described in section 4.3;

vii. rotate the AL-860 positioner so that the mirror on the AL-560 is visible from the theodolite;

viii. install the mirror assembly on the AL-560 platen and adjust the target similarly as required in step ii above;

ix. Make a visual check or use a level to verify the positioner axis is almost horizontal;

x. orient the theodolite toward the AL-560 keeping the line of sight horizontal, focus on the mirror and observe on the objective the respective position of the cross-hairs and the target on the mirror;

xi. adjust equally the three support jacks under the azimuth positioner until the cross-hairs coincide with the target. This operation must be done carefully observing the levels placed on the AL-860 platen surface to make sure the azimuth axis stays vertical. At this point, the line of sight of the theodolite is at the same height as the AL-560 axis (at the platen). Or in

other words, the line of sight of the theodolite crosses or meets the positioner rotation axis at the platen;

xii. repeat steps vi. and xi. until the cross-hairs and the target coincide while maintaining the axis vertical.

When this procedure is terminated, both axes, the AL-360 axis and the AL-560 axis are at the same height (at the platen). During the optical alignment, those axes will be oriented horizontal, parallel and coincident to form the range axis. The vertical adjustment stage of the AL-360 positioner might have to be readjusted to refine the height of the probe axis.

## 4.3 Roll Positioner (Supporting Mast) Initial installation

### 4.3.1 Introduction

For all antenna measurements, it is highly desirable that the AUT be mounted on the roll positioner so that the vertical azimuth axis or the centre of rotation of the azimuth positioner coincides (or intersects) as closely as possible with the phase centre of the AUT. If for a certain measurement setup there is a separation distance between the phase centre of the AUT and the centre of azimuth rotation, the distance between the probe and the phase centre of the AUT will vary during a measurement scan and the phase will consequently vary during the rotation and some amplitude errors might be introduced in the measurement. If, for instance, the centre of rotation is behind the phase centre of the antenna, the measured phase will pass by a minimum at boresight (when the azimuth angle of rotation is 0°), and will increase with rotation on either side. On the contrary, if it is ahead or in front of the phase centre, the phase value will pass by a maximum. However, if both centres coincide, the phase will be nearly constant during a scan. Consequently, it is necessary to keep the distance between the AUT and the probe constant during a measurement scan. To accomplish this, the position of the roll positioner must be adjusted by moving its supporting mast, the AL-560 mast, so that the phase centre of the AUT crosses or intersects the azimuth axis as nearly as possible. Obviously, if the correction is small enough and it is possible to reposition the AUT closer to or farther from the roll positioner platen to compensate for this situation, the repositioning of the mast will not be required.

The phase centre of an antenna is a region close to the aperture where the signal phase is constant. It is a principle that is not very rigorous; some feeds do not have a unique phase centre [6]. "A phase centre implies that the phase is relatively constant over some sphere surrounding the antenna, and for some antennas, this situation does not generally exist. On the other hand, over a major portion of the main lobe, the phase is usually constant over some spherical segment, whose centre is defined as the phase centre of the antenna".

The roll positioner is mounted over the azimuth positioner in the roll-over-azimuth configuration by means of an L-bracket as illustrated in Figure 1. This bracket is made of a metal mast, the AL-560 mast, bolted to a metal slotted base, the AL-560 mast slide. The roll positioner is on the top of the mast while the slotted base is attached to the azimuth positioner platen. The connection method between the mast and the base enables manual linear positioning of the mast

along the slots of the slotted base with a linear travel capability of 24 inches.

To perform the adjustment of the L-bracket, the position of the phase centre of the AUT and of the location of the azimuth axis must be known, i.e. the theodolite must be aligned onto the range axis and the optical axis intersecting the azimuth axis. However, if the spherical system is not yet aligned or if the theodolite is not aligned onto the range axis, the roll positioner could be setup approximately close to its final position and a pre-alignment of the spherical system done. If the system is aligned but the AUT configuration requires the positioner to be moved to satisfy the above requirements, a partial realignment will be required, because relocating the AL-560 mast brings a structural change to the positioner geometry, thus requiring realignment of at least the roll positioner if not all the spherical system, which in certain cases might be required.

### 4.3.2 Procedure for the Roll Positioner Initial installation

The purpose of this procedure is to move the AUT so that its phase centre intersects as closely as possible the azimuth axis. This is done by manually adjusting the position of the mast of the L-bracket along the slots of the base. This could be done with some precision only if the position of the phase centre is known and if the theodolite is aligned on the range axis and thus intersects the azimuth axis. On the contrary, if the alignment of the spherical system is not yet completed, has been lost for any reason, or the theodolite has been moved and its reference lost, or the phase centre is not known, the mast is adjusted approximately and an alignment is performed. This adjustment might be redone later if required. If the phase centre is unknown, a procedure described in Appendix B, will permit the establishment of the approximative position of the phase centre. In any case, if the mast position is changed, the system alignment must be checked and corrected if required. It is evident that after adjustment of the mast position, the counterweight at the other end of the slotted base of the L-bracket, must be readjusted for a smooth well balanced operation of the positioners.

The following procedure lists the steps required to adjust the mast of the L-bracket which supports the AL-560 positioner above the AL-860 positioner in a roll over azimuth configuration.

i. The theodolite is aligned on the range axis;

ii. a pencil mark is traced on the AUT to show the position of the phase centre. If it is not possible due to the configuration of the AUT, some means of indicating the location of the centre of phase should be devised;

iii. the azimuth positioner is rotated to a +/- 90° position and the theodolite is focussed on the AUT;

iv. the bolts holding the mast of the L-bracket to the metal slotted base are loosened and the mast is moved along the base until the phase centre mark on the AUT coincides with the theodolite cross-hairs. The bolts are then tightened. Care should be taken to move the base without rotating it to avoid changing the roll axis pointing direction. It is possible, if this modification is done carefully, to keep the alignment close to its original setting so less effort will be required later to recover the alignment of the roll positioner;

v. the counterweight located at the other end of the slotted base is adjusted to balance the weight of the roll positioner and of the AUT.

With this adjustment, the phase centre of the AUT should be very close to the azimuth axis. This is on the assumption that the AUT has a unique phase centre.

## 4.4 Alignment procedures

The procedures required to align the spherical positioner system are as follow:

i. selection of a unique plane perpendicular to the rails (section 4.4.1);

ii. alignment of the theodolite axis parallel to the rails (section 4.4.2);

iii. alignment of the azimuth positioner axis (section 4.4.3);

iv. alignment of the roll positioner axis (section 4.4.4);

v. alignment of the theodolite axis (section 4.4.5);

vi. alignment of the probe positioner axis (section 4.4.6);

vii. alignment of the probe axis(section 4.4.7);

viii. alignment of the AUT axis (section 4.4.8).

### 4.4.1 Selection of A Unique Plane Perpendicular to the Rails

The spherical positioner system, illustrated in Figure 1, presents several axes, which must be aligned: the probe and AUT roll axes must coincide together to form the range axis and must intersect orthogonally the (vertical) azimuth axis. All these axes must intersect a plane perpendicular to the rails, which is unique. This plane is parallel to the rails and approximately midway between them. Gravity must be in the plane so that all horizontal planes (which are perpendicular to this plane) are perpendicular to gravity. The first requirement in the optical alignment is to find the direction of that plane and align the theodolite into it. Once the theodolite is reset and locked in that direction, there is a possibility of several parallel planes, which are then available for the axis to be aligned to. As the alignment process progresses, the plane determination is refined and the plane position along with the range axis height are known accurately.

### 4.4.2 Alignment of the Theodolite Axis Parallel to the Rails

Aligning the theodolite to the direction, as already mentioned, is the first step of the optical alignment process. This step is a prerequisite because the probe may be moved along the rails between measurements and it is necessary to know the direction that the rails are pointing. This direction is an alignment parameter. The three degrees of freedom $\alpha_R$, $\beta_R$ and $y_R$ for the support rails are fixed and cannot be changed after the installation of the rails. They are use as reference for the direction of the rails.

The procedure to align the optical axis of the theodolite to the direction of the rails is described in detail in paragraph 3.2. Two methods are offered: the telescopic method and the

autocollimation method. In the first method, the telescope is focussed on a target point on the positioner and the line of sight is adjusted so that the reticule stays pointed to the target as the carriage travels along the rails. In the autocollimation method, the autocollimation dimension is added to the telescopic method so that one can observe how constant the rail direction is over the range of travel of the carriage.

When this procedure has been completed, the theodolite will be on an axis that is parallel to the rails. The theodolite will be reset to give a reading of 0° in azimuth when the line of sight is oriented in the direction of the rails. From this point, the theodolite will stay locked in that direction, but the precise height of the optical axis or the transverse position of this axis relative to the rails will not have been determined, though. The transverse position will be determined by the position of the AL-860 azimuth positioner **($y_8 \leftarrow$ Rails)** and the vertical position will be determined by the AL-560 roll positioner height **($x_5 \leftarrow$ REF)**, (paragraph 4.4.5).

### 4.4.3 Alignment of the Azimuth Positioner Axis

The next step in the alignment of the spherical measurement system consists of aligning the azimuth axis to vertical. The AL-860 axis $y_8$ position will be used as the transverse reference position of the range axis (and of the optical axis also) for measurements, because it cannot be easily moved in a transverse direction. The rails and the carriage were designed such that the positioner will be bolted onto the carriage into predetermined positions and stay there **($y_8 \leftarrow$ Rails)**. The AL-860 vertical axis will determine the location of the vertical plane that is perpendicular to the rails.

This axis may be set vertical or parallel to gravity by changing the two angular degrees of freedom $\alpha_8$ and $\gamma_8$. Introduced in paragraph 2.2.3, these angles are the angles that the azimuth axis makes with the vertical when the positioner is at two positions 90° apart. $\alpha_8$ and $\gamma_8$ are aligned with levels according to methods presented in paragraph 3.3 where a procedure to align the azimuth axis to be vertical using one level is described in detail. This procedure will ensure that the AL-860 axis is straight up and down and that it is adjusted parallel to gravity. Once the axis is set, only one vertical plane remains to reference the axes.

### 4.4.4 Alignment of the Roll Positioner Axis

The AL-560 roll positioner must be aligned horizontal and its axis must intersect the AL-860 azimuth axis orthogonally. The azimuth positioner is rotated to 180° with the Al-560 positioner facing the theodolite. The first part of this alignment is done using the theodolite set in autocollimation mode, i.e. focussed to infinity with the bright light turned on. The telescope, at this point, is aligned on one of the vertical planes in the direction of the rails. The roll axis is first aligned parallel to the optical axis, which is in turn translated to be coincident to the roll axis. This procedure is detailed in paragraph 4.4.4.2 below.

Next, the roll axis is translated in the transverse $y_5$ direction to intersect the azimuth axis. This is accomplished by rotating the azimuth positioner to 0°, the telescope is refocussed onto the target, and the distance between the reticule and the target, which is two times the intersection error is evaluated. After calculation of the intersection error, the roll axis and the theodolite are translated

in the transverse direction to compensate for this error of position, which is mid-way between the two noted positions. The two axes are made coincident again at this mid-way position. This technique is repeated until the intersection error becomes minimal or not discernible any more. This method is illustrated in Figure 13 and the detailed procedure is described in paragraph 4.4.4.3.

At this point, the roll axis is parallel and coincident to the optical axis and defines the range axis about which the probe axis will be aligned later.

#### 4.4.4.1 The Roll Axis Degrees of Freedom

The four degrees of freedom of the AL-560 axis, the pitch $\alpha_5$, the yaw $\beta_5$, the axis vertical displacement $x_5$ and the transverse displacement $y_5$ are commented on below. Refer to paragraph 2.2 for the discussion on the degrees of freedom and to Figure 2 for an illustration.

**Pitch $\alpha_5$:** it is aligned using the theodolite in autocollimation mode(**$\alpha_5 \leftarrow$ Theodolite).** The pitch angle is the angle between the axis of the AL-560 roll positioner and the optical axis in the vertical plane. It is determined by gravity (from the levelling of the theodolite). This parameter defines a horizontal plane that is perpendicular to gravity.

**Yaw $\beta_5$:** it is aligned using the theodolite in autocollimation mode (**$\beta_5 \leftarrow$ Theodolite)**. The yaw angle is the angle between the axis of the AL-560 roll positioner and the optical axis in the horizontal plane. The objective is to orient the axis of the AL-560 roll positioner parallel to the rails. The adjustment of the pitch and yaw are done together in a process that is described in paragraphs 3.5, 3.6 and 3.7.

**Vertical displacement $x_5$:** it is aligned with the theodolite focussed on the target. In the case of the AL-560, the vertical displacement cannot be adjusted **($x_5 \leftarrow$ REF)**. The height of the roll axis is taken to be the reference and determines then the height of the range axis. The theodolite will be vertically moved to the height of the target centre by adjusting its vertical stage **($x_T \leftarrow$ 560)**.

**Transverse displacement $y_5$:** it is aligned with the theodolite focussed on the target **($y_5 \leftarrow$ Theodolite)**. It is the transverse distance between the axes of the AL-860 and of the AL-560, this distance must be reduced to zero for both axes to intersect. The AL-560 is positioned such that its axis is coincident with the optical axis of the theodolite when it is intersecting the AL-860 (vertical) axis **($y_T \leftarrow$ 860)**.

#### 4.4.4.2 Alignment of the Roll Positioner Axis Parallel and Coincident to the Optical Axis

The procedure to align the AL-560 axis parallel and coincident to the line of sight of the theodolite is described in the following steps:

i. rotate the azimuth axis to position the AL-560 toward the theodolite, if not already there. This may be the best time to adjust the Orbit controller hardware offset angle for the AL-860 positioner to be at the 180° position in that orientation. The offset angle is adjusted so that when the azimuth positioner is at 0°, it is oriented in the (general) direction of the rails and

the AL-560 is facing the probe. The offset angle setting does not need to be extremely accurate because the Al-560 alignment device presents enough range of adjustment for its axis to be precisely aligned on the range axis;

ii. the two-way spindle target mirror is installed on the AL-560 turntable, oriented normal to the rotation axis and the target on the mirror is adjusted to intersect the axis of rotation. The detailed procedure for this step is described in section 3.4. After the execution of this step, one can go to step iii. or to step iv. below;

iii. a short cut to align both axes parallel could be taken in setting up the mirror in the above step ii. When the mirror is close to normal to the axis of rotation and the latter is also close to the line of sight (direction), the orientation of the axis could be achieved by spinning the positioner and adjusting the pitch and yaw using the spinning method described in paragraph 3.7. It might be required to readjust the mirror orientation, if the yellow circle is too large. It should be noted that for this step, the theodolite is set to autocollimation, and if the mirror had been adjusted normal to the to the axis of rotation in step ii. above, the lit cross would be concentric with the reticule of the theodolite, which is the goal of next step iv. After the execution of this step, go to step v.;

iv. the theodolite is set to autocollimation and oriented to 0° azimuth and to 0° vertical, and the roll axis is adjusted parallel to the line of sight of the theodolite. The detailed procedure for this step is described in section 3.5;

v. adjust both axes to coincide, i.e. the theodolite is focussed onto the mirror with the cross-hairs centred on the target. This situation presupposes that the centre of the target already intersects the axis of rotation as aligned according to the directions given in step ii. above. The detailed procedure for this step is described in section 3.6;

vi. this alignment process may be verified by spinning the AL-560. When the theodolite is set to autocollimation, and if the mirror has been adjusted exactly normal to the axis of rotation, the lit cross will be superposed onto the reticule in the telescope, which indicates that the rotation axis is parallel to the optical axis. If the mirror is not exactly normal, the lit cross will trace a small circle centred on the theodolite cross-hairs as illustrated in Figure 9 b).

vii. the above steps may need to be repeated until the verification above is satisfied. If repeated iterations do not remove small-randomized fluctuations in lit cross position, then these variations may be due to wobble rather than to inadequate alignment.

At this point, the AL-560 axis is horizontal (normal to gravity), parallel and coincident to the optical axis, but it is not yet intersecting the vertical azimuth axis.

#### 4.4.4.3 Alignment of the Roll Positioner to Intersect the Vertical Azimuth Axis

When this procedure is started, the azimuth axis is vertical and normal to gravity, the mirror target is concentric to the centre of rotation of the AL-560, the optical axis and roll axis are horizontal, parallel and coincident, but do not yet intersect the vertical axis. The following

procedure, illustrated in Figure 13, details the steps required to arrange the intersection of the two positioner axes:

i. rotate the azimuth positioner to 180°, if not already there;

ii. set the theodolite to 0° azimuth and to 0° vertical and focus onto the target on the mirror. Check that the reticule coincides with the target as adjusted according to the directives of the previous paragraph 4.4.4.2;

iii. rotate the azimuth positioner to 0° and evaluate the intersection error, which is half the distance between the optical axis and the roll axis or simply half the distance between the theodolite reticule and the centre of the target. The intersection error is very well illustrated in Figure 13, but it should be noted that this drawing is not to scale. Its purpose is only to show the principle of the technique used. The intersection error might only be a few millimetres long, while the mirror is 38 mm wide, so the roll axes in the two opposite azimuth positions are very close to each other and are visible in the eyepiece. Their relative position is estimated by observing the distance between the theodolite reticule and the target centre;

iv. adjust the linear transverse stage of the positioner alignment fixture to correct for the intersection error and bring the horizontal axis closer to intersecting the vertical axis;

v. Adjust the lateral translation stage of the theodolite, in the reverse direction, to bring the two horizontal axes to coincide again;

vi. repeat steps iii. to v. by alternating the azimuth rotation to 180° and to 0°, evaluating the intersection error and adjusting the translation stages.

When the intersection error becomes unnoticeable, the roll axis intersects the azimuth axis orthogonally. This sets the range axis about which the AL-360 axis will be aligned. This alignment procedure will be described in paragraph 4.4.6 below.

## 4.4.5 Alignment of the Theodolite Axis

### 4.4.5.1 The Optical Axis Orientation and its Placement on the Range Axis

The theodolite is continually being adjusted during the alignment process. At each step, the line of sight is more accurately aligned until the optical axis is set along the range axis at the end of the roll axis alignment exercise. Firstly, the theodolite horizontal orientation, $\alpha_T$, is determined at power on, where a 0° vertical reading means that the line of sight is horizontal and normal to gravity. Then the 0° azimuth, $\beta_T$, is set up where the optical axis is oriented in the direction of the rails as described in paragraph 4.4.2. The vertical displacement, $x_T$, of the theodolite is corrected during the adjustment of the roll axis coincident with the optical axis as described in paragraph 4.4.4.2, whereas the horizontal displacement, $y_T$, is corrected during the adjustment of the roll axis to intersect the vertical AL-860 axis as described in paragraph 4.4.4.3.

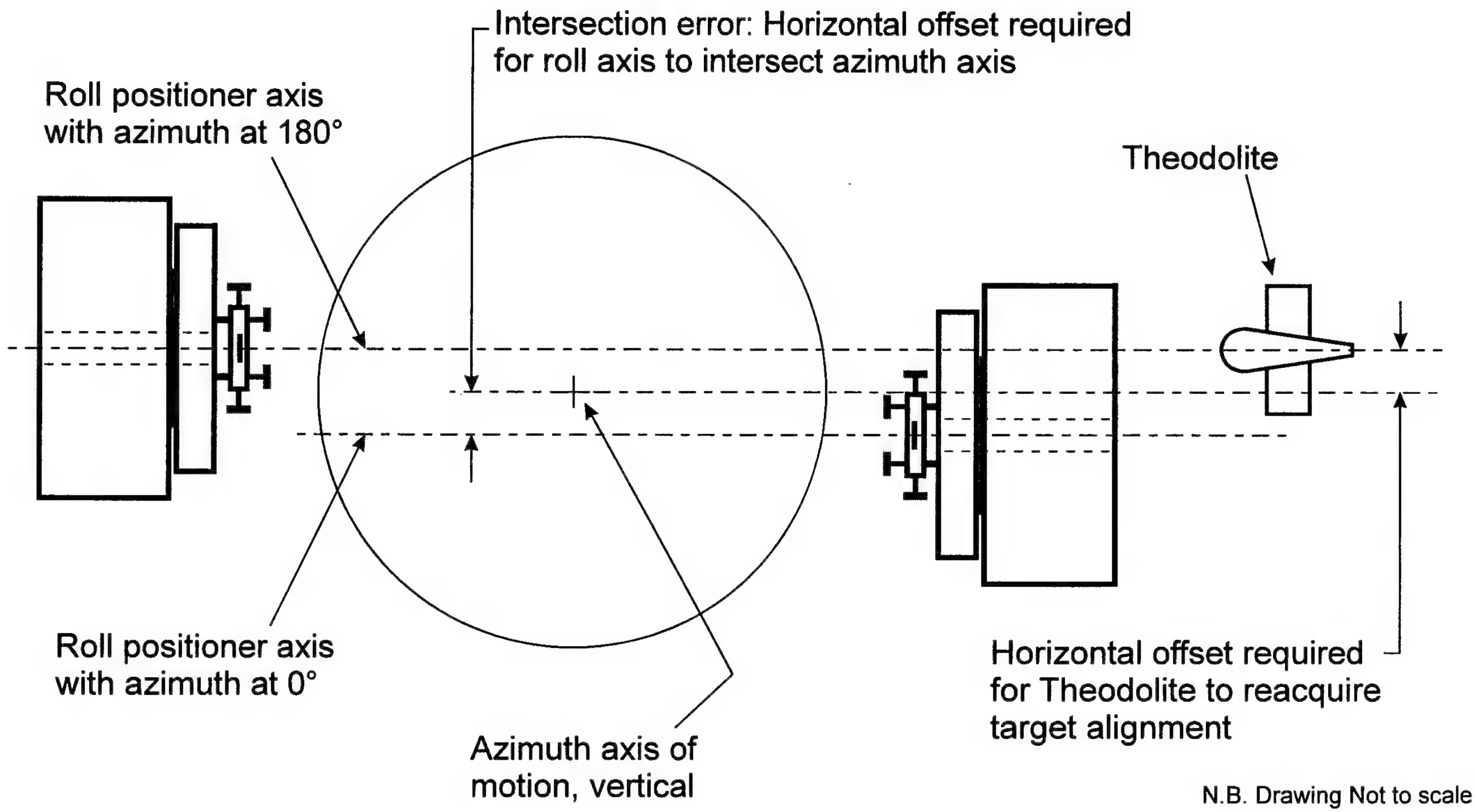



Figure 13 - Graphic Description of Intersection Error Between Roll Axis and Azimuth Axis (view from above) [5]

#### 4.4.5.2 The Theodolite Axis Degrees of Freedom

The four degrees of freedom of the theodolite axis, the pitch $\alpha_T$, the yaw $\beta_T$, the vertical displacement $x_T$ of the axis and the transverse displacement $y_T$ are commented below. Refer to paragraph 2.2 for the discussion on the degrees of freedom and to Figure 2 for an illustration.

**Pitch $\alpha_T$:** it is the alignment of the theodolite, which has the capability to accurately measure the direction of gravity (**$\alpha_T \leftarrow$ Gravity**). This defines a plane that is perpendicular to gravity and is the horizontal plane ($\alpha_T = 0$). This is done each time the theodolite is powered on.

**Yaw $\beta_T$:** this is the adjustment of the theodolite ($\beta_T = 0$), which places its axis parallel to the rails (**$\beta_T \leftarrow$ Rails**). This adjustment is done as in 4.4.2.

**Vertical displacement $x_T$:** This adjustment forces the axis of the theodolite to be collinear with the AL-560 axis, to be at least at the same height (**$x_T \leftarrow 560$**). It is done, as in 4.4.4.2, with the theodolite focussed on the target, by raising or lowering the theodolite until the target and the reticule are at the same height. This adjustment is done along with the roll axis alignment.

**Transverse displacement $y_T$:** This adjustment forces the axis of the theodolite to intersect the axis of the AL-860 vertical axis (**$y_T \leftarrow 860$**). It is done, as in 4.4.4.3, with the theodolite focussed on the target, by a simple transverse positioning adjustment. This adjustment is done along with the roll axis alignment.

### 4.4.6 Alignment of the Probe Positioner Axis

This alignment step is the last one for the physical alignment of the spherical positioner system. This is a simpler step than the roll positioner alignment step. The AL-360 must be aligned parallel and coincident with the range axis, which is equivalent to being aligned along the optical axis. Similarly to the roll axis, the first part of this alignment is done using the theodolite set in autocollimation mode. The telescope, at this point, is aligned on the range axis. The probe axis is first aligned parallel to the optical axis and then made coincident to it. This procedure is detailed in paragraph 4.4.6.2 below.

At this point, the probe and roll axes are parallel, coincident and horizontal or normal to gravity. They constitute the range axis. These axes intersect also orthogonally the vertical azimuth axis.

#### 4.4.6.1 The Probe Positioner Axis Degrees of Freedom

The four degrees of freedom of the AL-360 axis, the pitch $\alpha_3$, the yaw $\beta_3$, the vertical displacement $x_3$ of the axis and the transverse displacement $y_3$ , are commented below. Refer to paragraph 2.2 for the discussion on the Degrees of freedom and to Figure 2 for an illustration.

**Pitch $\alpha_3$:** it is aligned using the theodolite in autocollimation. It is determined by gravity (from the levelling of the theodolite) (**$\alpha_3 \leftarrow$ Theodolite**). This parameter defines a horizontal plane that is perpendicular to gravity.

**Yaw $\beta_3$:** it is aligned using the theodolite in autocollimation. The objective is to orient the axis of the AL-360 roll positioner parallel to the rails, but more precisely, parallel and coincident to the range axis, which was defined during the alignment of the roll axis **($\beta_3 \leftarrow$ Theodolite)**. The adjustment of the pitch and yaw are done together in a process that is described in paragraphs 3.5, 3.6 and 3.7. With the adjustment of $\alpha$ and $\beta$ both axes will be parallel.

**Vertical displacement $x_3$:** it is aligned with the theodolite focussed on the target. This is the vertical displacement between the optical axis of the theodolite **($x_3 \leftarrow$ Theodolite)** and the AL-360 axis. This axis is moved vertically to be in the same horizontal plane as the theodolite axis, or in other words, the AL-560 axis or the range axis.

**Transverse displacement $y_3$:** it is aligned with the theodolite focussed on the target. It is the transverse distance between the theodolite axis **($y_3 \leftarrow$ Theodolite)** and the AL-360 axis; this axis is moved horizontally until both axes are in the same vertical plane. This is done along with the vertical displacement, by focussing on the target and by translating the positioner until the target and the theodolite cross-hairs are concentric. With this adjustment of $x_3$ and $y_3$, the axes of the AL-360 and of the AL-560 will be collinear.

#### 4.4.6.2 Alignment of the Probe Positioner Parallel and Coincident to the Optical Axis

The procedure to align and bring the AL-360 axis parallel and coincident to the line of sight of the theodolite is described in the following steps:

i. rotate the azimuth axis to ±90° to position the AL-560 off the line of sight of the theodolite;

ii. the two-way spindle target mirror is installed on the AL-360 turntable, oriented normal to the rotation axis and the target on the mirror is adjusted to intersect the axis of rotation. The detailed procedure for this step is described in section 3.4. After the execution of this step, one can go to step iii. or to step iv. below;

iii. a short cut to align both axes parallel could be taken in setting up the mirror in the above step ii. When the mirror is close to normal to the axis of rotation and the latter is also close to the line of sight (direction), the orientation of the axis could be achieved by spinning the positioner and adjusting the pitch and yaw using the dynamic method described in paragraph 3.7. It might be required to readjust the mirror orientation, if the yellow circle is too large. It should be noted that for this step, the theodolite is set to autocollimation, and if the mirror had been adjusted normal to the to the axis of rotation in step ii. above, the lit cross would be concentric with the reticule of the theodolite, which is the goal of next step iv. After the execution of this step, go to step v.;

iv. the theodolite is set to autocollimation and is oriented to 0° azimuth and to 0° vertical and the probe axis is adjusted parallel to the line of sight of the theodolite. The detailed procedure for this step is described in section 3.5;

v. adjust both axes to coincide, i.e. the theodolite is focussed onto the mirror with the cross-hairs centred on the target. This situation presupposes that the centre of the target already

intersects the axis of rotation as aligned according to the directions given in step ii. above. The detailed procedure for this step is described in section 3.6;

vi. this alignment process may be verified by spinning the AL-360. When the theodolite is set to autocollimation, and if the mirror has been adjusted exactly normal to the axis of rotation, the lit cross will be superposed onto the reticule in the telescope, which indicates that the rotation axis is parallel to the optical axis. If the mirror is not completely normal but close to normality, the lit cross will trace a small circle centred on the theodolite cross-hairs as illustrated in Figure 9 b).

vii. the above steps may need to be repeated until the verification above is satisfied.

At this point, the AL-360 axis is horizontal (normal to gravity), parallel and coincident to the optical axis. This concludes the alignment of the three axes of rotation of the spherical positioner system. Axis coincidence, axis intersection and orthogonality are the three aspects of the positioning system geometry, which were discussed in the previous sections of this report. This chapter will be concluded with a discussion on the alignment of the probe antenna and of the antenna under test (AUT). The mirrors are removed from the platforms and replaced by the antennas with their support brackets. Only the theodolite, still aligned on the range axis, is left. It is used as a guide to align the antennas, to measure the linear and angular orientation errors, and to bring whatever possible correction is required to decrease them.

### 4.4.7 Alignment of the Probe Axis

This alignment step is done after the completion of the alignment of the spherical positioner system axes. The mirror, which is magnetically attached to the base of the antenna support bracket mounted over the turntable, is removed and put aside. The probe antenna is mounted on its holding plate, which is then installed on top of the steel posts of the antenna support bracket. The theodolite, which is still aligned on the range axis, will be used to align the probe along this axis. In this process, the pointing direction of the probe will be aligned as accurately as possible parallel to the range axis and the probe centerline, and collinear to this axis as well.

The antenna support is a bracket assembly especially designed to be attached to the positioner platen or the turntable. A partial view of this bracket is shown in Figure 6 a). This view shows how the mirror is used for the alignment. The mirror, magnetically attached to the centre of the base plate of the bracket assembly, is surrounded by four steel posts. The function of these posts is to hold the probe mounting plate, after the removal of the mirror. The probe is attached to this plate at the waveguide flange. This mounting hardware presently has limited adjustment capability, but it has been precisely machined to limit, at best, displacement errors about the range axis. These errors, however, can be measured very precisely with the theodolite.

Once the probe is mounted on the positioner, the position and orientation of the probe about the range axis (and the optical axis) are observed and measured with the theodolite. The position of the waveguide feed at the throat of the horn and of the horn aperture in relation to the range axis are determined. This determination is done by reading with the theodolite key features of the probe, either the angles at the four corners of the feed and of the aperture or simply the angular

position of the flat faces. The opposite angles in azimuth and vertical orientation are subtracted to determine the centre position of the horn at the throat and at the aperture. The calculator program introduced in section 3.4.2 and described in Appendix A can be used for this calculation. If the resulting centre values are not 0° azimuth and 0° vertical, the probe is not centred on the range axis and the pointing direction of the horn is at an angle with the range axis. A method to measure the two components of the error angle in pointing direction, in the azimuth and in the vertical direction, is described in section 4.4.7.2. This algorithm, however, has not been implemented yet into the calculator program.

It is possible to slightly reduce the antenna alignment error by introducing some shimming where the probe attaches to the plate. The probe is connected to a coaxial-to-waveguide adaptor, which in turn is attached to the holding plate by the flange screws. By putting shims of variable thickness under the side or the corner of the flange, it is possible to change the position of the horn about the range axis and also to modify the pointing direction of the probe. Although it is not possible to completely correct the probe alignment error, improvements could be reached by trial and error. It is not very easy to do and great patience is required from the personnel doing the work.

#### 4.4.7.1 The Probe Degrees of Freedom

The five degrees of freedom of the probe antenna, the pitch $\alpha_P$, the yaw $\beta_P$, the vertical displacement $x_P$, the transverse displacement $y_P$ and the polarization $\gamma_P$, are commented on below. The down-range position of the probe antenna $z_P$ is not included here because this position does not matter particularly, provided the separation of the AUT and the probe is appropriate for the type of measurements being undertaken. Refer to paragraph 2.2 for the discussion on the degrees of freedom and to Figure 2 for an illustration. Presently these degrees of freedom are fairly limited in their extent with the type of antenna support available. At the time of writing of this report, there is no provision to accurately adjust the positioning of the probe along the first four degrees of freedom described below. Probe positioning relies only on the precision of the mounting hardware machining. However, a replacement antenna support mechanism could remedy these shortcomings.

**Pitch $\alpha_P$:** it is aligned using the theodolite **($\alpha_P \leftarrow$ Theodolite)**. This is the pitch angle of the probe horn with the optical axis, and it can be done by sighting the antenna using the theodolite and vertically centring the waveguide feed at the throat of the horn within the outer bounds of the horn.

**Yaw $\beta_P$:** it is aligned using the theodolite **($\beta_P \leftarrow$ Theodolite)**. This is the yaw angle of the probe horn with the optical axis, and it can be done by sighting the antenna using the theodolite and horizontally centring the waveguide feed at the throat of the horn within the outer bounds of the horn. The adjustment of the pitch and yaw angles are done together. The objective is to orient the horn pointing direction parallel to the optical axis. With the adjustment of $\alpha_P$ and $\beta_P$, the throat and the aperture of the horn will appear concentric in the theodolite eyepiece.

**Vertical displacement $x_P$:** it is aligned using the theodolite **($x_P \leftarrow$ Theodolite)**. This is the vertical position of the probe horn, and it can be done by sighting the antenna using the theodolite and centring the probe horn vertically on the optical axis.

**Transverse displacement $y_P$:** it is aligned using the theodolite (**$y_P$ ← Theodolite**). This is the horizontal position of the probe horn, and it can be done by sighting the antenna using the theodolite and centring the probe horn horizontally on the optical axis. This is done along with the vertical displacement by translating the probe until the throat and the aperture of the horn are concentric in the eyepiece and their centres coincide with the optical axis.

**Polarization $\gamma_P$:** it is the polarization of the probe. It is usually aligned using gravity as a reference. Some point or feature of the antenna is chosen and set horizontal or vertical, either perpendicular or parallel to gravity, using a level or the theodolite, and then reported.

#### 4.4.7.2 The Pointing Direction of a Horn

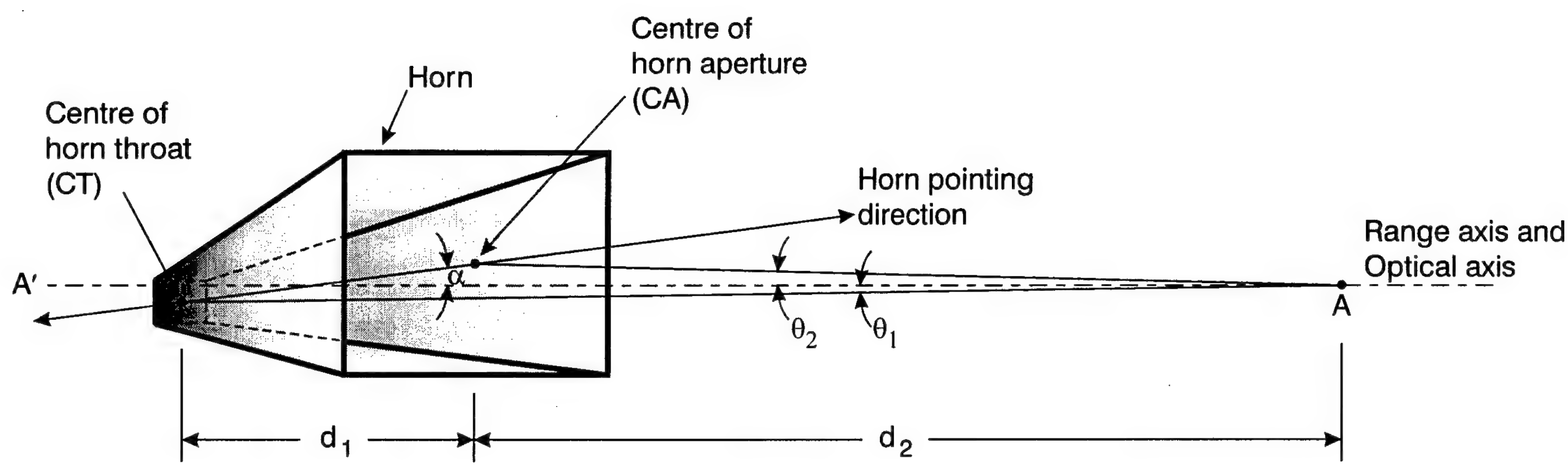
When a horn such as the probe is mounted on a positioner, it is ideally installed so that its centerline is coincident with the range axis, but due to the mechanical imperfection of its supporting mechanism, it is not always possible to accomplish this. Because of this, an error in the pointing direction of the horn with respect to the range axis is introduced. An algorithm to evaluate this error in both directions i.e. in azimuth and vertical direction has been developed.

For this development, let us consider the geometry of Figure 14. This geometry shows $\theta$ angles for the vertical orientation, but the algorithm can also be applied to angular errors in the azimuth or horizontal direction. Let a small horn located along the range axis A-A′ with its centre line making a certain angle $\alpha$ with the range axis (and optical axis) in the vertical direction. Let the theodolite be located at A with the optical axis coincident with the range axis. Let $d_1$ be the horn length and $d_2$ be the distance from the horn aperture to the theodolite.

With the theodolite focussed and pointed to the centre of the throat of the horn, an angle $\theta_1$ between the optical axis and the centre of the throat position is measured. Then with the theodolite focussed and pointed to the centre on the horn aperture, the angle $\theta_2$ is also measured and noted. It must be emphasized that these angles ($\theta_1$ and $\theta_2$), as measured by the theodolite, have each two components, i.e. an azimuth and a vertical component. Furthermore, it should be noted that the sign of the azimuth angles input into the algorithm is positive for the angles measured to the right of the optical axis (0°) and negative in the reverse direction, i.e. for values less than 360°. Therefore, for azimuth angles between 180° and 360°, the quantity 360 must be subtracted from their values to get the right signs and values to be used in the formula below. As the theodolite angles in the vertical direction are already signed, no conversions are required for them.

Using the geometric relations of the law of triangles, an expression for $\tan\alpha$ has been developed. A more detailed development of this expression can be found in Appendix C.

$$\tan\alpha = \frac{d_2}{d_1}\tan\theta_2 - \frac{d_1 + d_2}{d_1}\tan\theta_1$$




$d_1$ : horn length or distance between horn throat and horn aperture
$d_2$ : distance between horn aperture and theodolite
$\theta_1$ : theodolite angle between range axis and center of horn throat
$\theta_2$ : theodolite angle between range axis and center of horn aperture
$\alpha$ : horn pointing direction or angle between horn axis and range axis

$\alpha$ is calculated with the following relation:

$$\tan\alpha = \frac{d_2}{d_1}\tan\theta_2 - \frac{(d_1 + d_2)}{d_1}\tan\theta_1$$

Figure 14. Horn Pointing Angle Error Geometry

However, because $d_2 >> d_1$, the above relation can be reduced to a simpler expression such that:

$$\tan\alpha = \frac{d_2}{d_1}(\tan\theta_2 - \tan\theta_1)$$

Moreover, as the two theodolite angles are small, the above expression can even be reduced to this much simpler expression:

$$\alpha = \frac{d_2}{d_1}(\theta_2 - \theta_1)$$

It should be remembered that each variable can have positive or negative values.

It is easy to determine, with the theodolite, the position of the centre line of the horn, which crosses the throat at point CT and the aperture at point CA. Physical features of the horn at the throat and at the aperture are measured and, with the help of the calculator program, the precise coordinates of the points CT and CA on the horn centre line are calculated. The distance $d_1$ is easily measured because of its short length, but the distance $d_2$, which may be several metres long, is more difficult to measure with good precision. With the position of CT and CA known, the composite angles (azimuth and vertical components) of $\theta_1$ and $\theta_2$ are measured and noted. The relation above can be calculated for both the azimuth and the vertical directions and the values of the horn pointing directions with respect to the range axis are determined.

## 4.4.8 Alignment of the Antenna Under Test Axis

This alignment step is done after the alignment of the probe antenna because it is usually impossible to see the probe with the theodolite after the mounting of the AUT on the roll positioner. All the discussion about the alignment of the probe antenna at paragraph 4.4.7 apply to the alignment of the AUT with the exception of the down range position of the antenna in the z direction or the range axis direction. As discussed in section 4.3 above, the AUT must be positioned such that its phase centre is coincident with (or very close to) the azimuth axis.

At this point in the optical alignment of the spherical positioner system, this adjustment is already done because, as indicated in paragraph 4.3.1, the alignment of the roll positioner is lost if the AL-560 Mast is displaced to provide for the requirement that the phase centre coincides with the rotation axis. Before the proper optical alignment of the positioners on the range axis, the AUT must Be pre-mounted on the positioner and the location of its phase centre in relation to the rotation axis checked, measured and the support bracket adjusted as described in section 4.3 to satisfy the above installation requirement of the AUT.

### 4.4.8.1 The AUT Antenna Degrees of freedom

The six degrees of freedom of the AUT , the pitch $\alpha_A$, the yaw $\beta_A$ , the vertical displacement $x_A$, the transverse displacement $y_A$, the down range position $z_A$ and the polarization $\gamma_A$ are commented below. Refer to paragraph 2.2 for the discussion on the degrees of freedom and to Figure 2 for an illustration. Presently these degrees of freedom are fairly limited in their extent with

the type of antenna support available. At the time of writing of this report, there is no provision to accurately adjust the positioning of the AUT along the first four degrees of freedom described below. AUT positioning relies only on the precision of the mounting hardware machining. However, a replacement antenna support mechanism could remedy these shortcomings.

**Pitch $\alpha_A$:** it is aligned using the theodolite (**$\alpha_A \leftarrow$ Theodolite**). This is the pitch angle of the antenna with the optical axis, and it can be done by sighting the antenna using the theodolite and centring the waveguide feed vertically (when visible) within the outer bounds of the antenna. It may be also be done with levels.

**Yaw $\beta_A$:** it is aligned using the theodolite (**$\beta_A \leftarrow$ Theodolite**). This is the yaw angle of the antenna with the optical axis, and it can be done by sighting the antenna using the theodolite and centring the waveguide feed horizontally (when visible) within the outer bounds of the antenna. The adjustment of the pitch and yaw angles are done together. The objective is to orient the antenna pointing direction parallel to the optical axis.

**Vertical displacement $x_A$:** it is aligned using the theodolite (**$x_A \leftarrow$ Theodolite**). This is the vertical position of the antenna, and it can be done by sighting the antenna using the theodolite and centring the AUT vertically on the optical axis.

**Transverse displacement $y_A$:** it is aligned using the theodolite (**$y_A \leftarrow$ Theodolite**). This is the horizontal position of the antenna, and it can be done by sighting the antenna using the theodolite and centring the AUT horizontally on the optical axis. This is done along with the vertical displacement by translating the AUT until its axis coincides with the optical axis.

**Down range position $z_A$:** Unlike the probe antenna, the position of the AUT (relative to the azimuth rotation axis) is important. Usually the AUT will be positioned such that the expected position of the phase centre will be coincident with the azimuth positioner axis. It is necessary to measure the distance from the positioner axis to some reference point on the AUT. The pattern measurements of the AUT will indicate the location of the phase centre with respect to the axis of the azimuth positioner. These two measurements can be used to yield the location of the phase centre with respect to the chosen reference point on the AUT.

**Polarization $\gamma_A$:** it is the polarization of the AUT. It is usually aligned using gravity as a reference. Some point or features of the antenna is chosen and set horizontal or vertical, either perpendicular or parallel to gravity, using a level or the theodolite, and then reported.

# 5 - Assessment of Measurement Errors

## 5.1 Introduction

Errors in the measurement of antenna properties fall into the categories of electrical and mechanical. They are introduced by imperfect probe location, distortion of the radiated field by the measurement equipment, inaccurate measurement of the fields, and computational approximations. Since the subject of this report is the mechanical alignment of the spherical (far-field) measurement system, the following discussion will concern mainly the inaccuracies of the positioning of the probe (relative to the AUT). Errors arise from lack of precision during the axis alignment process as stated, of the measurement of the actual positions of the probe and the antenna to be tested after installation on their respective positioners, and also result from deflection and vibration of the probe and the AUT during testing.

Angle measurement errors from a number of sources must be considered in determining the accuracy of an antenna range [6]. For the purpose of this discussion, the error sources can generally be included in one of the following classifications:

1. Geometric Error,
2. Shaft-Position Error,
3. Deflection Error.

Additional direction errors which can be caused by phase and amplitude variations in the field over the test aperture are not in the scope of this discussion.

## 5.2 Geometric Error

If the positioners of Figure 1 were geometrically perfect, the azimuth positioner axis would be exactly normal to the roll positioner axis, and the axes of the roll and probe positioners would be coincident. The geometrically perfect antenna test system would also have an antenna (AUT) installed on the roll positioner turntable and a probe antenna installed on the probe positioner turntable so that the coordinate system of each of the two antennas would be exactly aligned with the coordinate systems of their positioners.

An actual antenna range consists of physical components that approach the above requirements, but geometric and mechanical errors will always exist. Each antenna measurement system will have 3 separate geometric errors which can be identified as described in the following paragraphs.

1. **Coordinate axis alignment error.** Improper alignment of the antenna coordinate system with the antenna positioner coordinate system. Since the antenna coordinate system is defined with respect to a mechanical reference on the antenna while the roll axis is mechanically related to the positioner, some misalignment between the two will always exist in practice. This error will occur with both the AUT and the probe antennas.

2. **Orthogonality error.** Non-orthogonality of the two motion axes of the roll-azimuth positioner that supports the AUT.

3. **Collinearity error**. Non-coincidence of the AUT antenna/positioner axis and the probe antenna/positioner axis. In a perfect system, these two axes are coincident and that axis is referred to as the range axis.

Section 5.7 of Reference [6] presents a detailed discussion of these types of mechanical errors and proposes a method for the analysis of the misalignment errors and the calculation for a direction $\varphi$, $\theta$ (roll and azimuth direction) of an antenna having geometric misalignment errors for each of the three separate geometric errors described above.

Two major random errors are associated with an axis of rotation. These are the wobble and the runoff. The wobble is an angular variation as the axis is rotated (an axis by definition should point in a constant direction). The extent of this wobble can be measured optically, but because this motion can result from a combination of structural deformation and bearing imprecision, it cannot be adjusted, but merely monitored. The second error, the runoff, is a displacement (translation) error of the axis within the bearings.

The rails, which are strong, heavy, straight and stable have been adjusted as well as possible to be parallel and horizontal (normal to gravity). They are fixed and cannot be moved. However, the rails are not perfect, there are three independent errors related to them due to their installation. These also affect two other errors. These five errors are listed below:

roll error: it appears when one rail rises or falls while the other is maintained at its position or moves in the opposite direction;

pitch error: it appears when both rails rise or fall together, yielding a non-zero pitch angle relative to the horizontal;

yaw error: it appears when the direction of the rails changes relative to its initial direction (the rails are not straight);

vertical displacement: it results from a non-zero pitch angle maintained over a distance along the rails;

transverse displacement: it results from a change in the direction of the rails maintained over a distance along the rails.

These rails errors do not have any impact if neither the probe nor the AUT positioners is translated along the rails after an optical alignment has been completed. There would be an impact, however, if pattern measurements at different AUT-probe separation distances were required, and it was decided not to perform an optical realignment after each translation of the probe or the AUT along the rails to a new position. In this case, the accuracy of the placement of the two antennas relative to each other would be dependent on the straightness and alignment of the rails.

## 5.3 Shaft-Position Error

The shaft position angle of the antenna positioner is usually determined by synchro transmitter or inductosyn encoders. The shaft position error is the difference between the true shaft angle and the shaft angle as indicated by the encoder or synchro readout system. Over 360 degrees of axis rotation, the readout error is typically from 0.05° to less than 0.01°, depending on the type of encoding system used. The total shaft position error with an encoder installed consists of the encoder error, encoder housing deflection, encoder coupling error, and differential temperature effects.

The positioner accuracy is not of particular concern when measuring gain and sidelobes, but is clearly a factor in boresighting [7]. Boresighting is the process that locates the electrical axis of the system with respect to an identifiable mechanical axis. The electrical axis is in the direction of the peak of the main beam and it may vary in position with frequency. Typical figures of 0.1° of backlash of the drive train of the positioner and 0.03° accuracy of the synchro that feeds the antenna position back to the controller make the measurement of beamwidths and boresighting with a consistent direction of rotation essential, thereby cancelling most of this error. The DDARLing system angle readout is 0.005°, about an order of magnitude greater in accuracy [8]. This is obtained using the inductosyn angle position sensor.

Positioner accuracy also affects the accuracy of the more sophisticated pattern analysis procedures. A consistent shift in angles results in a simple phase slope that is easily recognizable in the derived phase data. Random errors in angle have an effect on the computed distribution that is dependent on sidelobe level. A good rule of thumb is that angular errors of less than 0.06 times the sidelobe width are almost inconsequential. This usually corresponds to about 0.04 beamwidths. Of course, this angle accuracy limit may be overridden by boresighting requirements.

## 5.4 Deflection Error

Positioner deflection errors are caused principally by changes in the forces applied to the positioner turntables and by expansion and contraction of structural members due to changing temperature gradients. This is prevalent in outdoor systems where there is differential heating by the sun. This error may be ignored in indoor systems, particularly those employed in an environment where the temperature is controlled during measurement and when the test antennas are of a small weight.

It shall be noted that for several of the mechanical accuracies, a correction is possible if the amount of the inaccuracy can be determined. Thus, for polarization mismatch, the test antenna coordinated system will often be defined by the on-axis linear polarization direction. Hence the probe rotation will, to some extent, be compensated for by a corresponding rotation of the test antenna reference system and the cross polarization caused by the probe rotation will vanish in the on-axis direction.

Readers who want to carry out a deeper investigation into this subject, may consult reference [9] to find a detailed discussion of computer simulations of the mechanical accuracies which were carried out for some measurement set-ups. Results are given in a table and commented extensively.

# 6 - Conclusion

This report has described a custom designed system and novel techniques developed at DREO to perform a precision alignment of a spherical antenna range using optical instrumentation. Adequate precision has been obtained to allow near-field measurement of antennas up to the millimetre-wave region. The optical equipment used for the alignment includes precision levels, an autocollimation theodolite, mirrors with a high precision target, and alignment and positioning devices for supporting optical tools and positioners. Significant modifications and improvements were made to the optical hardware, particularly the target mirror, and also to the rail system and positioner carriages, and to the theodolite support system. Novel alignment techniques developed include: the way that the equipment has been integrated into a system to achieve the desired accuracy; the overall alignment concept; methods to determine the location of axes of rotation; and the development of methods to align the positioner axes so that they are collinear, or perpendicular and intersecting. Major characteristics of this technique include the precise setting of the intersection of the axes to a fraction of a millimetre, the setting of axes orthogonality to within a few arc-seconds, and the direct measurement of the roll and probe axes stability under motion.

However, this method needs some improvements which include considering the over-all alignment activity to improve the accuracy where possible, but also more importantly, to shorten the execution time which at present, may be fairly prolonged. It is hoped that, with repeated execution of this activity and better understanding of the alignment process, these shortcomings will be resolved. A method should also be developed to rapidly recover the alignment when the optical reference is lost or when the theodolite must be removed and later replaced on its stand and realigned on the range axis without having to go through the complete process. Another point which may be the object of additional work in the future is the conduct of a mechanical alignment error analysis and determination of the effects of the errors on the antenna measurement accuracy. Finally, to improve on the positioning and alignment of the antennas along the range axis, it is intended to redesign the front plate of the antenna support and/or the entire platen frame assembly (for antenna support) to insure precise and reproducible attachment of the antenna and probe on the positioner platens. This will require the design of additional adjustment mechanisms to enable the adjustment degrees of freedom (mentioned above in the text) to place an antenna and orient its direction of propagation along the range axis, i.e. aligning the antenna axis collinear with the range axis.

# References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# Appendix A – Calculator Program "THEOD"

## A.1 Introduction

This program processes the (azimuth and vertical) theodolite readings taken during the optical alignment of the spherical ORBIT positioner system.

To adjust the autocollimation mirror normal to a positioner axis, theodolite readings are taken when the positioner is rotated to position $0°$ and to $180°$. The theodolite is then set to the mid-azimuth and mid-vertical positions, which are calculated by the program.

This process is also used to find where to move the centre of the target on the mirror to coincide with the positioner axis (in telescopic mode, i.e. when the theodolite is focussed on the mirror).

The range of angles is small. It is the range of azimuth and vertical angles measured when looking at the mirror, either telescopically or in autocollimation. The azimuth angles values are either close to $360°$ or to $0°$, decreasing from $360°$ turning to the left or increasing from $0°$ toward the right. The vertical angle values are close to $0°$, increasing toward $90°$ looking up or decreasing toward $-90°$ looking down.

The program also calculates the resulting centre angle (in sec's.) in an azimuth-vertical spherical space. The theodolite is at the centre of the sphere and the distance from the theodolite to the mirror is the sphere radius. The program calculates the length (in mm) at the mirror covered by the centre angle using a radius given in metres. This length could represent either the distance from the positioner axis to the mirror target centre, when the theodolite is used in telescopic mode, or the offset between the positioner axis and optical axis (at the mirror), when the theodolite is used in autocollimation mode.

In addition the program calculates the coordinates where the second point (in the $0°$-$180°$ measurement method, in autocollimation mode) should be moved so the centre of the yellow circle (traced by the autocollimation cross) is displaced over the centre of the theodolite cross-hairs. The theodolite is set to this new position and the positioner axis orientation is changed so that the yellow circle seen in the theodolite eyepiece is centred over the black cross-hairs.

## A.2 Running the program

To Start the program, enter the following calculator command:

**XEQ THEOD** press the **XEQ** key (top right key on the keypad) and the menu key below the program name "**THEOD**" displayed on the calculator display. The six square black dots on the illustration below represent menu keys on the first row.

The calculator display is:

| | | | | | |
|---|---|---|---|---|---|
| **XEQ _** | | | | | |
| **.END.** | **LENG** | **THEOD** | | | |
| ■ | ■ | ■ | ■ | ■ | ■ |

The program starts and a menu is displayed requesting input for angles in D.MS format, which is **Deg.MMSSSS**

where:

| | |
|---|---|
| Deg | degrees |
| . | decimal period |
| MM | minutes (2 digits) |
| SSSS | seconds in hundreds (or SS.SS) |

The calculator display is:

| | | | | | |
|---|---|---|---|---|---|
| **ENTER** | | **ANGLES■DMS** | | **FMT** | |
| **AZ1** | **VER1** | **AZ2** | **VER2** | **RANG** | |
| ■ | ■ | ■ | ■ | ■ | ■ |

To enter an angle or a variable, do the following:

- input its value in the X register in the D.MS format, and
- press the menu key below the variable name.

These variables are not zeroed at program entry, they retain the values of the previous run, so if some variables have not changed, it is not required to reenter all of them again.

The input variables are:

| | |
|---|---|
| AZ1, VER1 | Theodolite azimuth and vertical readings with positioner at 0° |
| AZ2, VER2 | Theodolite azimuth and vertical readings with positioner at 180° |
| RANG | The range in metres (theodolite/mirror distance). |

When all the required input values are entered, the program is continued by pressing the **R/S** key (lower row to the right).

After calculation, a **results menu** is displayed showing 6 output variables.

| X:-0.1234567 | | | | | |
|---|---|---|---|---|---|
| **AZIMU** | **VERTI** | **AXISA** | **AXISV** | **LENG** | **RANG** |
| ■ | ■ | ■ | ■ | ■ | ■ |

Pressing one of the six menu keys, will display the selected result.

| | | |
|---|---|---|
| AZIMU | Mid-azimuth value | (AZIMUTH) |
| VERTI | Mid-vertical value | (VERTICA) |
| AXISA | Azimuth value used to set the theodolite to move the positioner axis parallel to the optical axis | (AXISAZ) |
| AXISV | Vertical value used to set the theodolite to move the positioner axis parallel to the optical axis | (AXISVER) |
| LENG | Length in mm at the mirror | (LENMM) |
| RANG | Distance between the theodolite and the mirror in metres (input value) | (RANGM) |

Note: The items in parentheses represent the text used by the program to output the calculated values to the display.

If the key below AZIMU is pressed the following result is displayed. The number is interpreted to means that the mid-azimuth value displayed in DMS format is 0° 6 min. 31.5 sec's.

| AZIMUTH=0.0631500 | | | | | |
|---|---|---|---|---|---|
| **AZIMU** | **VERTI** | **AXISA** | **AXISV** | **LENG** | **RANG** |
| ■ | ■ | ■ | ■ | ■ | ■ |

Pressing one of the calculator keys below when the program is idle will redirect the

program as follows:

| | | |
|---|---|---|
| ↑ | GOTO | the starting point of the program |
| ↓ | GOTO | the **LENGTH** entry point |
| **EXIT** | STOP | the program |

Two other variables are also calculated:

| | |
|---|---|
| ANGS | Centre angle in sec's. |
| ANGD | Centre angle in D.MS format |

These program variables and all the others can be examined with the following calculator commands:

1. **RCL** variable name

or

2. **■PGM.FCN ■PGM.FCN VIEW** variable name

A second entry to the program, **LENGTH,** is used to calculate a length at the mirror subtended by an angle from the theodolite. It requests an angle value in arc-sec's and a range length (distance between the theodolite and the mirror) in metres. To start at this entry point:

1. Enter the calculator command:

   **XEQ LENG** or

2. When the program is idle press the ↓ key.

A menu is displayed requesting values to be input.

| **FIND LENGTH IN MM** | | | | | |
|---|---|---|---|---|---|
| **ANGS RANG** | | | | | |
| ■ | ■ | ■ | ■ | ■ | ■ |

Enter an angle in seconds and a range in metres and continue the program by pressing the **R/S** key.

After calculation, the **results menu** is displayed showing the 6 variables as shown above in the previous page.

## A.3 Algorithm

1. Enter the 4 angles AZ1, VER1, AZ2, VER2 in D.MS format
2. Convert from D.MS to DEG
3. Mid_AZ = (AZ1 + AZ2)/2
4. If the azimuth angles are on either side about the origin (0°, 360°) then:
   Mid_AZ = (Mid_AZ + 180) MOD 360
5. Mid_VER = (VER1 + VER2)/2
6. Convert Mid_AZ and Mid_VER from DEG to D.MS
7. Mid_angle (sec's) = 3600*SQRT(Mid_AZdeg**2 + Mid_VERdeg**2)
   or if Mid_AZ greater than 180°,
   Mid_angle (sec's) = 3600*SQRT((Mid_AZdeg-360)**2 + Mid_VERdeg**2)
8. Convert Mid_angle to RAD
9. Enter the distance between the theodolite and the mirror (Range_m) in metre
10. LENGTHmm (at the mirror) = Mid_angle (rad) * Range_m * 1000
11. Move the positioner axis parallel to the optical Axis:

    Mid angle values (in the angular or autocollimation plan) indicate the position of the centre of the yellow circle in relation to the optical axis (or the angle between the positioner axis and the optical axis).

    The AL-860 positioner (in the 0°-180° method) is at the 2nd position (at 180°), that 2nd position (azimuth and vertical readings) is subtracted from the position of the centre of the yellow circle. Results of the calculation are stored in the two variables AXISAZ and AXISVER. The theodolite is set to that new calculated position and the positioner axis orientation is changed so that the centre of the yellow circle, as seen in the theodolite eyepiece, is moved over the centre of the theodolite cross-hairs. This will make both axes, the positioner axis and the optical axis, parallel to each other.

# A.4 Calculator Program Listing

| | | |
|---|---|---|
| **01** | **LBL "THEOD"** | |
| 02 | MVAR "AZ1" | Setup data entry menu |
| 03 | MVAR "VER1" | |
| 04 | MVAR "AZ2" | |
| 05 | MVAR "VER2" | |
| 06 | MVAR "RANGEM" | |
| 07 | VARMENU "THEOD" | |
| 08 | TONE 8 | |
| 09 | "ENTER ANGLES■ | |
| 10 | ├"D.MS FMT" | |
| 11 | AVIEW | Query for input values |
| 12 | STOP | |
| 13 | EXITALL | |
| 14 | RCL "AZ1" | |
| 15 | RCL "AZ2" | Start with AZ angles |
| 16 | HMS+ | Add x+y in **HourMinSec** format |
| 17 | →HR | Change value to HOUR format |
| 18 | 2 | |
| 19 | ÷ | (AZ1+AZ2)/2 in deg |
| 20 | STO 01 | M_AZdeg stored in Reg 1 |
| 21 | →HMS | Change value to HMS format |
| 22 | STO "AZIMUTH" | M_AZdeg stored in D.MS fmt |
| 23 | RCL "VER1" | same for ver1 & ver2 |
| 24 | RCL "VER2 | |
| 25 | HMS+ | |
| 26 | →HR | |
| 27 | 2 | |
| 28 | ÷ | |
| 29 | STO 02 | M_VERdeg stored in Reg 1 |
| 30 | →HMS | |
| 31 | STO "VERTICA" | M_VERdeg stored in D.MS fmt |
| 32 | 180 | |
| 33 | RCL "AZ1" | check on which side of 0-180 line |
| 34 | X>Y? | are the azimuth angles |
| 35 | GTO 01 | |
| 36 | R↓ | x=180 |
| 37 | RCL "AZ2" | |
| 38 | X<Y? | |
| 39 | GTO 04 | both AZ1 & AZ2 values between 0 & 180 |
| **40** | **LBL 02** | both AZ1 & AZ2 are either side of 0-180 line |
| 41 | R↓ | x=180 |
| 42 | RCL "AZIMUTH" | |
| 43 | XEQ 03 | M_AZdms=(M_AZdms+180) MOD 360 |
| 44 | STO "AZIMUTH" | |
| 45 | 180 | |
| 46 | RCL 01 | y=180, x=M_AZdeg |
| 47 | XEQ 03 | M_AZdeg=(M_AZdeg+180) MOD 360 |
| 48 | STO 01 | |
| 49 | GTO 04 | Continue |
| **50** | **LBL 01** | AZ1 (180-360), AZ2(?) |
| 51 | R↓ | x=180 |
| 52 | RCL "AZ2" | |
| 53 | X>Y? | |
| 54 | GTO 04 | both AZ1 & AZ2 between 180 & 360 |
| 55 | GTO 02 | both AZ1 & AZ2 are either side of 0-180 line |
| **56** | **LBL 03** | Subroutine |
| 57 | + | |
| 58 | 360 | |
| 59 | MOD | (AZ+180) MOD 360 |
| 60 | RTN | |
| **61** | **LBL 04** | Start calculation of centre angle |
| 62 | 180 | |
| 63 | RCL 01 | y=180, x=M_AZdeg |
| 64 | X<Y? | |
| 65 | GTO 05 | if AZ > 180 substr. 360 |
| 66 | 360 | |
| 67 | - | |
| **68** | **LBL 05** | |
| 69 | X↑2 | x=(AZdeg-360)**2 or AZdeg**2 |
| 70 | RCL 02 | x=M_VERdeg |
| 71 | X↑2 | VER**2 |
| 72 | + | |
| 73 | SQRT | SQRT(AZ**2+VER**2) |
| 74 | →HMS | |
| 75 | STO "ANGDMS" | Centre angle in D.MS |
| 76 | →HR | |
| 77 | 3600 | |
| 78 | x | |
| 79 | STO "ANGSEC" | Centre angle in sec's |
| 80 | GTO 06 | Jump around LENGTH entry |
| **81** | **LBL "LENGTH"** | LENGTH entry |
| 82 | MVAR "ANGSEC" | DATA entry menu |
| 83 | MVAR "RANGEM" | |
| 84 | VARMENU "LENGTH" | |
| 85 | TONE 6 | |
| 86 | "FIND LENGTH IN" | |
| 87 | ├"MM" | |
| 88 | AVIEW | Query for input values |
| 89 | STOP | |
| 90 | EXITALL | |
| **91** | **LBL 06** | Continue |
| 92 | RCL "ANGSEC" | |
| 93 | 3600 | |
| 94 | ÷ | |
| 95 | →RAD | angle in RAD |
| 96 | RCL "RANGEM" | range in metre * 1000 |
| 97 | 1000 | |
| 98 | x | |
| 99 | x | |
| 100 | STO "LENMM" | = Length in mm |
| 101 | 180 | Find where to move autocollimation axis |
| 102 | RCL "AZIMUTH" | |
| 103 | X<Y? | |
| 104 | GTO 07 | |
| 105 | 360 | |
| 106 | HMS- | AZIMUTH-360 |

```
107  LBL 07

108  RCL "AZ2"
109  X<->Y                  Exchange X &Y
110  HMS-                   AZ2-AZIMUTH MOD 360 -> AXISAZ
111  360
112  MOD
113  STO "AXISAZ"

114  RCL "VER2"
115  RCL "VERTICA"
116  HMS-                   VER2-VERTICAL -> AXISVER
117  STO "AXISVER"

118  "AZIMUTH"              Output MENU Preparation
119  KEY 1 XEQ 11
120  "VERTICAL"
121  KEY 2 XEQ 12
122  "AXISAZ"
123  KEY 3 XEQ 13
124  "AXISVER"
125  KEY 4 XEQ 14
126  "LENGTH IN MM"
127  KEY 5 XEQ 15
128  "RANGM"
129  KEY 6 XEQ 16

130  KEY 7 GTO "THEOD"      ↑ KEY to restart
131  KEY 8 GTO "LENGTH"     ↓ KEY to go to LENGTH entry
132  KEY 9 GTO 99           EXIT KEY to terminate program
133  MENU
134  TONE 9

135  LBL 20

136  STOP                   waiting loop
137  GTO 20
138  STOP
```

**OUTPUT MENU EXECUTION**

```
139  LBL 11

140  VIEW "AZIMUTH"
141  RTN

142  LBL 12

143  VIEW "VERTICA"
144  RTN

145  LBL 13

146  VIEW "AXISAZ"
147  RTN

148  LBL 16

149  VIEW "RANGEM"
150  RTN

151  LBL 15

152  VIEW "LENMM"
153  RTN

154  LBL 14

155  VIEW "AXISVER"
156  RTN

157  LBL 99

158  CLMENU
159  EXITALL

160  .END.
```

# Appendix B – Phase Centre of An Antenna

## B.1 Introduction

In this appendix, a technique to measure the phase centre of an antenna is described. An antenna is mounted on the roll positioner and a measurement cut is done to measure the phase over a major portion of the main lobe. An algorithm, described below, has been implemented in a Microsoft EXCEL spreadsheet program. The program requires for its operation some measurement parameters such as the transmitting frequency, the phase of the signal when the antenna is pointing at boresight (when the azimuth positioner is at rotation angle 0°), and a distance D between the aperture plane (or a suitable mechanical reference) and the axis of rotation.

The program requires also two columns of data which represent the phase values measured at the azimuth angle where the measurements were taken. A third column, calculated by the program, gives the position of the phase centre from the reference plane. The program then generates a graphic displaying the resulting phase centre values calculated as a function of the azimuth (or rotation) angle. The graph is analysed, interpreted and an average value of the phase centre is taken from that graph. This value is considered to be the AUT phase centre value used for the alignment of the roll positioner.

## B.2 Algorithm for the Determination of the Phase Centre of An Antenna

For the determination of the algorithm, let us consider the geometry of Figure 15. Let a small antenna be placed with its phase centre located at O′ with its main lobe directed toward the probe at P along the range axis OP, which is in the plane of the paper [6]. Let the centre of rotation at O be in a plane normal to the paper. If the azimuth positioner is rotated by an angle φ, the antenna moves to location O″ and a phase deviation is measured by the probe due to the change of path of length δ

$$r + \Delta \doteq R + \Delta - \delta$$

or

$$\delta \doteq R - r$$

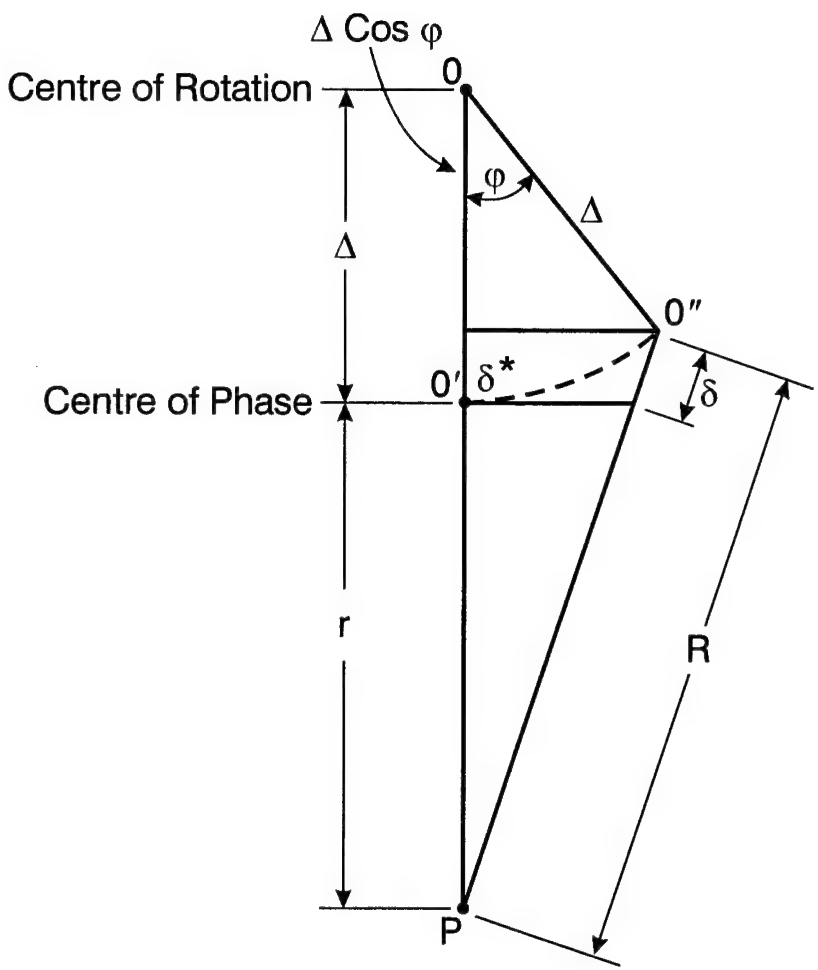
The phase deviation in degrees of the measured phase front from the phase at boresight is given by $\phi'' - \phi' = 360\,\frac{\delta}{\lambda}$ where the $\phi$'s are the measured electrical phase in degrees at both antenna positions as indicated in Figure 15, and $\lambda$ is the wavelength in cm.

For a geometry where $\Delta$ is small and $r \gg \Delta$,

$$\delta \approx \delta^{*} = \Delta - \Delta\cos\varphi$$

Thus, δ is given by

$$\delta = (1 - \cos\varphi)\,\Delta$$




Legend:

0 : Centre of Rotation
0′ : Phase centre location of a small antenna
0″: Phase centre location after a rotation φ
φ : Angle of rotation of azimuth axis
Δ : Separation 0-0′ and 0-0″ between centre of rotation and centre of phase
r : Distance from probe to centre of phase; r >> Δ
R : New distance from probe to centre of phase after a rotation φ of the azimuth positionner
δ : Change in distance after a rotation φ
P : Probe location

Figure 15 - Geometry illustrating phase deviation measured by probe at long range when Δ is small.

"It is evident from the above equations that the resolution in determination of $\Delta$ is dependent on the width of the angular sector of $\varphi$ over which the measurement is made. Evidently if $\Delta$ is zero, i.e. if the phase centre is located over the centre of rotation, $\delta$ must be zero on the assumption of a circular phase front in the plane of exploration. If the field should be identically circular in the plane of exploration, the phase of the signal measured by the probe would be constant with rotation in $\varphi$. In practice, of course, $\delta$ will not be zero for all $\varphi$" [6].

The purpose of this exercise is to find a method to measure the position of the phase centre of an antenna relative to the axis of the AL-860 azimuth positioner and to reduce their separation or the length $\Delta$ to the smallest value possible. Because the position of the front face of the AUT (or some other identifiable antenna feature) can be measured accurately with the theodolite, the above relation could be modified to include distances from a reference plane such as the antenna aperture.

Let $D$ be the distance between the reference plane, usually the aperture plane (or any suitable mechanical reference) and the axis of rotation, and let $d$ be the position of the phase centre from the reference plane. Refer to Figure 16 for an illustration of the geometry and an indication of the positive direction for $D$ and $d$.

Consider the distance and wavelength measurements to be in centimetres. Using the wavelength relation below where $\lambda$ is related to the frequency in GHz

$$\lambda = \frac{30}{F}$$

and the relations for $\delta$ and $\Delta$ above, the following relation is derived.

$$d = D + \frac{(\phi'' - \phi')}{12\,F\,(1 - \cos\varphi)}$$

This relation has been implemented in a Microsoft EXCEL spreadsheet program. Figure 16 illustrates the front page of this program where the formula, a diagram showing the phase centre geometry and instructions on the program usage are displayed. As an example, Figure 17 illustrates a resulting graph of the phase centre calculation for a portion of the main beam of a horn. An average value of the result is estimated and this value is taken as the phase centre value used for the alignment during the initial installation of the roll positioner supporting mast. This example represents a situation where the centre of rotation is behind the phase centre and the value of d is positive. So the corrective action to implement will consist in moving the AUT *d* cm back toward the roll positioner platen, or if not possible because of mechanical restrictions, in moving the "560 Mast" *d* cm back using the procedure described in the previous section.

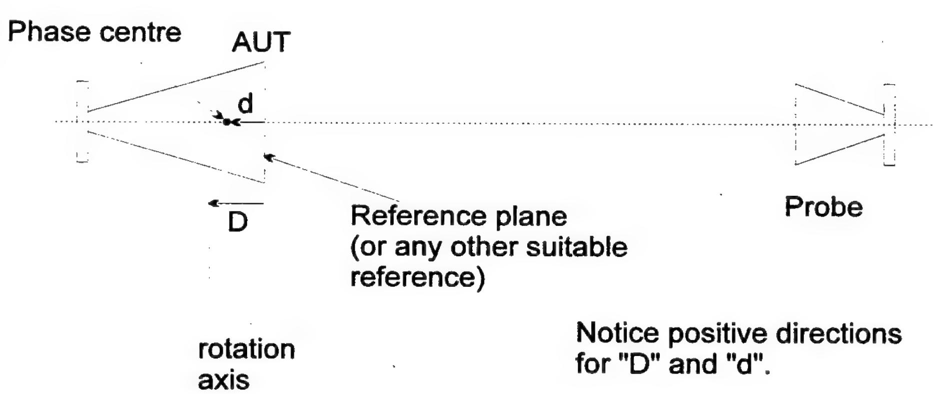
# PHASE CENTRE POSITION

Formula:

$$d = D + \frac{\dfrac{30 * (phi - phi0) * pi}{freq * 180}}{2 * pi * (1 - \cos( Az*pi/180 ))}$$

| | |
|---|---|
| d | : position of phase centre from reference plane (usually the aperture plane) in cm. Notice the positive direction on the diagram below. |
| freq | : frequency in GHz at which the measurement is made |
| D | : distance in cm between the aperture plane (or any suitable mechanical reference) and the axis of rotation . Notice the positive direction |
| Az | : azimuth angle in degrees |
| phi | : phase measured in degrees at the specified azimuth angle |
| phi0 | : phase measured in degrees at azimuth angle of 0 degree |

## PHASE CENTRE GEOMETRY




Instructions:

-----------------

1. Do an azimuth cut of the AUT at a frequency of interest. Note that only the phase is needed.
2. Choose a mechanical reference point on the AUT from which you want to know the phase centre position. For a horn, this is usually the mouth.
3. Measure the distance between your reference point and the (azimuth) rotation axis.
4. Create a table of azimuth vs phase from the measurement. Select azimuth angles in the main beam only.
5. Enter the table below in the "Az" and phi "columns".
6. Enter: "D", "phi0", and "freq".
7. The phase centre position is given in the column "d" from your reference point.
8. The graphics on next sheet shows the result. Note that an average value must be chosen.

Figure 16 - Microsoft EXCEL Program for the Phase Centre Calculation

## B.3 Procedure for the Measurement of the Phase Centre of An Antenna

The procedure for the measurement of the phase centre of an antenna is described in the following steps below:

i. the AUT is mounted on the roll positioner;

ii. the distance *D* between a reference plane of the AUT, usually the aperture plane (or any suitable mechanical reference ) and the axis of rotation of the azimuth positioner is measured;

iii. a measurement cut over a major portion of the main beam of the antenna is done;

iv. the frequency F, the phase $\phi$ and the angle of rotation $\varphi$ of each measurement points are recorded and transferred to the Microsoft EXCEL spreadsheet program and the resulting graph is printed;

v. the graph is analysed, interpreted and a phase centre value for the AUT is determined.

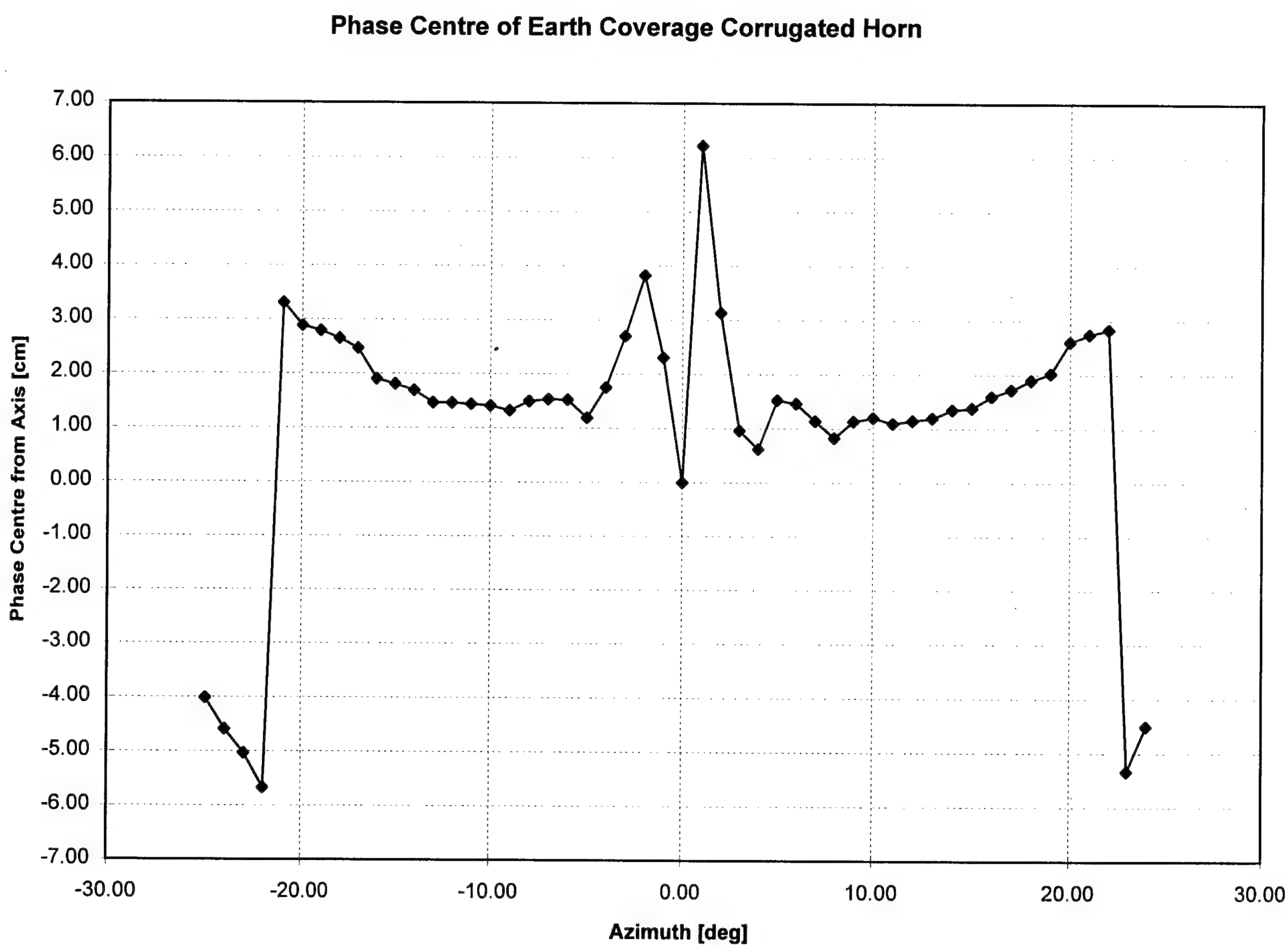



Figure 17 - Phase Center Graphical Representation Example

# Appendix C – Horn Pointing Angle Error Calculation

## C.1 Introduction

This appendix describes the mathematical development of the formula for the horn pointing angle error calculation introduced in section 4.4.7.2. Figure 18 is a remake of Figure 14 to emphasize the relation between angles and lengths in the geometry illustrated in the Figure. The following new elements are introduced for the formula development:

$h_1$: distance between the A′-A axis (optical axis) and CT (centre of the horn at the throat)
$h_2$: distance between the A′-A axis and CA (centre of the horn at the aperture)
$d_3$: distance along A′-A axis from the point of intersection of the axis of the horn with the optical axis to the horn aperture.

Referring to Figure 18, the sense of the angles $\alpha$ and $\theta$ and of the distances $h$ and $d$ have been defined. Figure 18 shows the direction of the above angles and distances except for the distances $d$. What is observed in the figure is two coupled / linked rectangular coordinates systems. One of these has its origin at the pivot point inside the horn and the other at the pivot at the theodolite. It should be noted that the variables $\theta$, $h$ and $d$ can be negative or positive.

## C.2 Coordinate System at the Horn

1. Let the origin of the coordinate system for the horn be the point on the optical axis where it intersects with the axis of the horn. The actual location of this origin will depend on the orientation of the horn and its position relative to the optical axis.

2. Let positive $\alpha$ be defined as the pitch angle of the horn relative to the (horizontal) optical axis measured counterclockwise from the line joining the pivot points (origins). Thus, for $\alpha$=0, the horn points in a direction parallel to the optical axis and toward the theodolite.

3. Let positive $d$ be defined as the distance measured along the optical axis toward the theodolite from the horn origin. (Note that for $90° < \alpha < 270°$, $d$ will be negative.)

4. Let positive $h$ be the height of the centre of the throat ($h_1$) or the aperture ($h_2$) of the horn above the horizontal optical axis.

## C.3 Coordinate System at the Theodolite

1. Let positive $\theta$ be defined as the angle measured clockwise from the horizontal (optical) axis toward the centre of the throat ($\theta_1$) or the aperture ($\theta_2$) of the horn. This is consistent with the theodolite coordinate system and angle algebraical sign.

2. Let positive $d$ be defined as the distance measured along the optical axis toward the horn from the theodolite origin.

3. Let positive $h$ be the height of the centre of the throat ($h_1$) or the aperture ($h_2$) of the horn above the horizontal axis.

From the figure and the above discussion, and using the conventional relations of the law of triangles, it can be seen that

$$h_1 = (d_1 + d_2) \tan \theta_1 \tag{1}$$

$$h_2 = d_2 \tan \theta_2 \tag{2}$$

and

$$\tan \alpha = \tan(\pi + \alpha) = \frac{h_2}{d_3} = \frac{h_1}{d_3 - d_1} \tag{3}$$

Substituting (1) and (2) into (3) gives

$$\tan \alpha = \frac{d_2}{d_3} \tan \theta_2 = \frac{(d_1 + d_2)}{d_3 - d_1} \tan \theta_1 \tag{4}$$

and solving for $d_3$ using the right side of (4) gives

$$\frac{1}{d_3} = \frac{d_2 \tan \theta_2 - (d_1 + d_2) \tan \theta_1}{d_1 d_2 \tan \theta_2} \tag{5}$$

which may be substituted back into the left side of (4) to give

$$\tan \alpha = \frac{d_2}{d_1} \tan \theta_2 - \frac{(d_1 + d_2)}{d_1} \tan \theta_1 \tag{6}$$

Since $d_2 >> d_1$, equation (6) can be reduced to

$$\tan\alpha \approx \frac{d_2}{d_1}(\tan\theta_2 - \tan\theta_1)$$

and at the limit, because $\theta_1$ and $\theta_2$ are small angles, the relation can be further reduced to

$$\alpha \approx \frac{d_2}{d_1}(\theta_2 - \theta_1)$$

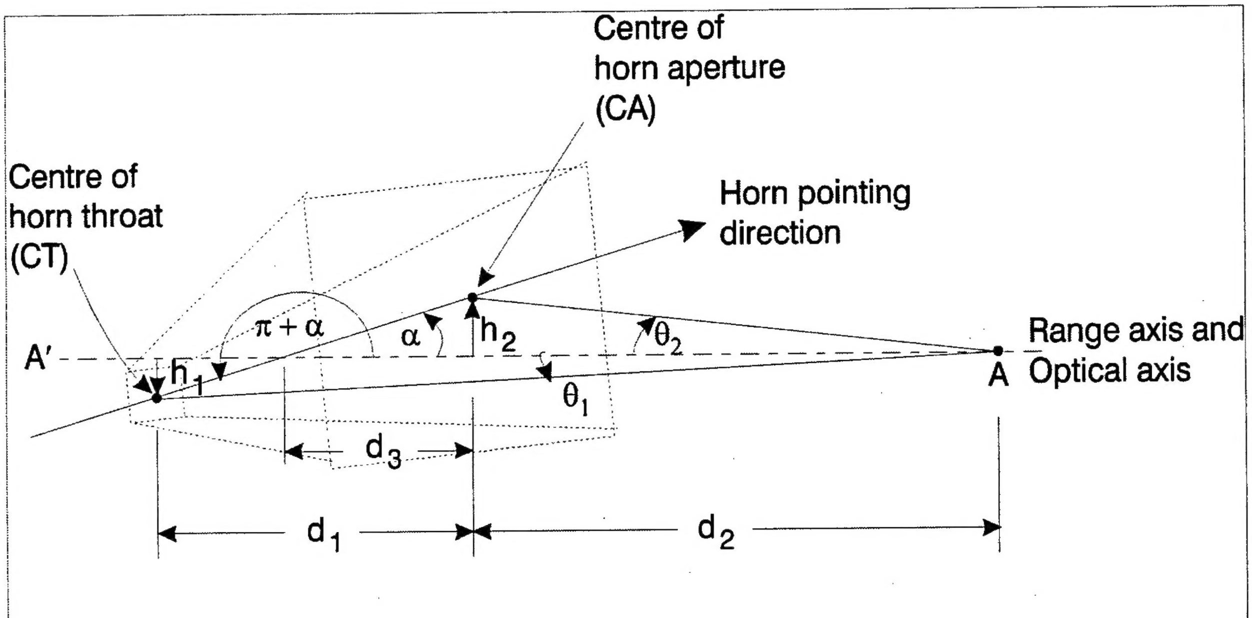



Figure 18 - Horn Pointing Angle Error Calculation

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